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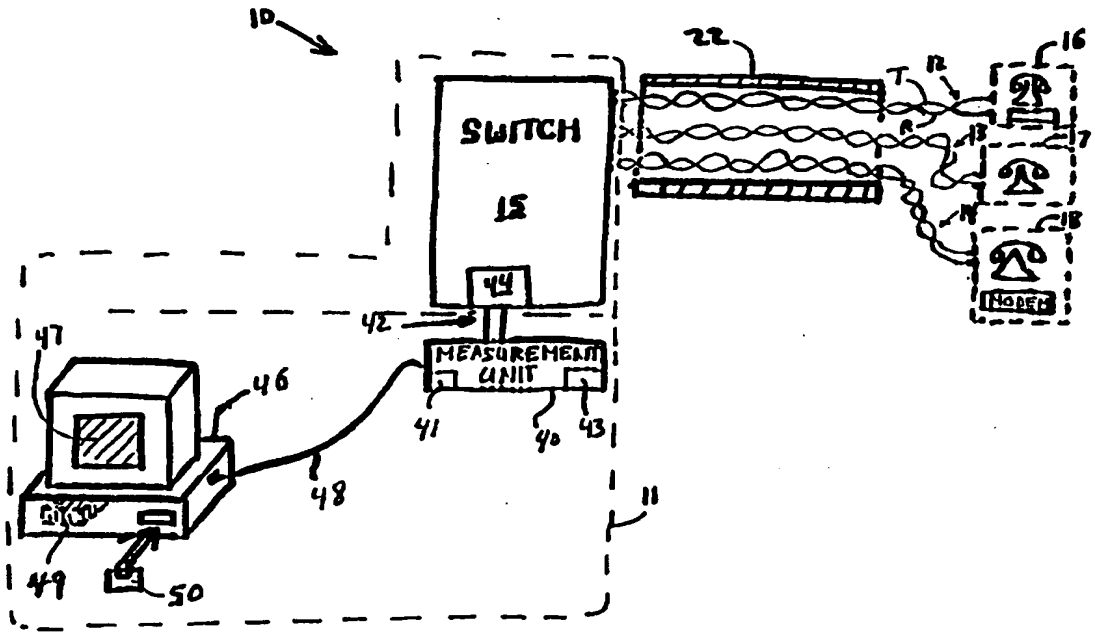

(57) Abstract

A method determines a structure of a subscriber line. The method includes searching a reference set for a match between the subscriber line and a model line of the reference set and identifying that the subscriber line has a specific physical structure. The match is based on electrical properties of the lines. The act of identifying is responsive to finding a match with one of the model lines that has the specific physical structure.

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DETERMINING THE PHYSICAL STRUCTURE OF SUBSCRIBER LINES

This is a continuation-in-part of Application No. U.S. Application No. 09/294,563, filed April 20, 1999.

Background of the Invention

This application relates generally to communications networks, and more particularly, to determining electrical properties of multi-wire communication lines.

Recently, there has been an increased demand for the subscriber lines of plain old telephone services (POTS's) to carry high-speed digital signals. The demand has been stimulated by home access to both the Internet and distant office computers. Both types of access typically employ a POTS line as part of the path for carrying digital signals.

POTS's lines were built to carry voice signals at audible frequencies and can also carry digital signals as tone signals in the near audible frequency range. Modern digital services such as ISDN and ADSL transmit data at frequencies well above the audible range. At these higher frequencies, POTS's lines that transmit voice signals well may transmit digital signals poorly. Nevertheless, many telephone operating companies (TELCO's) would like to offer ISDN and/or ADSL data services to their subscribers.

Telephone lines between a TELCO switch and subscribers' premises are frequent sources of poor performance at the high frequencies characteristic of ISDN and ADSL transmissions. Nevertheless, high cost has made widespread replacement of these subscriber lines an undesirable solution for providing subscribers with lines capable of supporting ISDN and ADSL. A less expensive

alternative would be to repair or remove only those subscriber lines that are inadequate for transmitting high-speed digital data.

To limit replacement or repair to inadequate lines, TELCO's have placed some emphasis on developing methods for predicting which subscriber lines will support data services, such as ISDN and ADSL. Some emphasis has been also placed on predicting frequency ranges at which such data services will be supported. Some methods have also been developed for finding faults in subscriber lines already supporting data services so that such faults can be repaired.

Current methods for predicting the ability of subscriber lines to support high-speed digital transmissions are typically not automated, labor intensive, and entail test access at multiple points. Often, these methods entail using skilled interpretations of high frequency measurements of line parameters to determine data transmission abilities. At a network scale, such tests are very expensive to implement.

The present invention is directed to overcoming or, at least, reducing the affects of one or more of the problems set forth above.

Summary of the Invention

In a first aspect, the invention provides a method of determining a physical structure of a subscriber line. The method includes searching a reference set for a match between the subscriber line and a model line of the reference set and identifying that the subscriber line has a specific physical structure. The match is based on electrical properties of the lines. The act of identifying is responsive to finding a match with one of

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the model lines that has the specific physical structure.

In a second aspect, the invention provides a method of qualifying a subscriber line for a data service. The method includes searching a reference set of model lines for a best match to a subscriber line by comparing sets of electrical properties and determining that the subscriber line has a specific physical structure. The act of determining is responsive to the best matching model line having the specific physical structure. The method also includes disqualifying the subscriber line for the data service, in part, in response to determining that the specific physical structure corresponds to a disqualified line.

In a third aspect, the invention provides a method of providing a data service. The method includes searching for a match between electrical properties of a subscriber line and a model line of a reference set and determining whether the subscriber's line is qualified for the data service. The act of determining is based in part on whether the best matching model line has one of a bridged tap and a mixture of gauges. The method also includes performing a business action in response to determining that the subscriber's line is qualified.

In a fourth aspect, the invention provides a data storage device that stores an executable program of instructions for causing a computer to perform one or more of the above-described methods.

Various embodiments use test accesses, which provide data on low frequency electrical properties of subscriber lines, to make predictions about high frequency performance.

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Brief Description of the Drawings

Other features and advantages of the invention will be apparent from the following description taken together with the drawings in which:

FIG. 1 shows a portion of a POTS network having a system for detecting faults in subscriber telephone lines;

FIG. 2A shows a first measuring setup for making one-ended electrical measurements on a subscriber telephone line;

FIG. 2B is an equivalent circuit for the measuring setup of FIG. 2A;

FIG. 2C shows a second measuring setup for making one-ended electrical measurements on a subscriber telephone line;

FIG. 3 illustrates signal distortions produced by the test bus and standard voice test access;

FIG. 4 shows a split pair fault in a subscriber line;

FIG. 5 shows how a splice error can produce a split pair fault;

FIG. 6A shows a phase measurement signature of a resistive imbalance on a subscriber line;

FIG. 6B shows a phase measurement signature of a split pair fault on a subscriber line;

FIG. 7 is a flow chart illustrating a method of detecting faults on subscriber lines with the system of FIGs. 1, 4, and 5;

FIG. 8 is a flow chart illustrating a method of qualifying subscriber lines with the method of FIG. 7;

FIG. 9 shows a method of providing high speed data services using the methods of FIGs. 7 and 8;

FIG. 10A-10E show exemplary subscriber lines having different gauge mixes;

FIG. 11 shows a subscriber line with a bridged tap;

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FIG. 12A-12E shows exemplary structures of subscriber lines having one bridged tap;

FIG. 13 is a flow chart for a method of determining the specific physical structure of a subscriber line from a reference set;

FIG. 14 is a flow chart for a method of finding a best match between a subscriber and model lines;

FIG. 15 is a flow chart for a method of qualifying subscriber lines; and

FIG. 16 is a flow chart for a business method of providing high-speed data services to subscribers.

FIG. 17 is a flow chart for a stacked method of detecting bridged taps using auxiliary variables;

FIG. 18A shows predicted and actual signal attenuations of nominal subscriber lines;

FIG. 18B shows predicted and actual signal attenuations of non-nominal subscriber lines;

FIG. 18C shows predicted, shifted predicted, and actual signal attenuations for an exemplary nominal subscriber line;

FIG. 19 shows an exemplary decision tree;

FIG. 20 illustrates the action of the rules of the decision tree of FIG. 19 on a set of subscriber lines;

FIG. 21 is a flow chart illustrating a method of creating the decision trees with machine learning methods; and

FIG. 22 is a flow chart for a method of determining the branching rules of the decision tree illustrated in FIGs. 19-20.

Description of the Preferred Embodiments

MEASUREMENT AND TEST APPARATUS

FIG. 1 shows a portion of a POTS network 10 that has a system 11 for detecting faults in subscriber lines 12-

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14. The subscriber lines 12-14 connect subscriber units 16-18, i.e., modems and/or telephones, to a telephony switch 15. The switch 15 connects the subscriber lines 12-14 to the remainder of the telephone network 10. The switch 15 may be a POTS switch or another device, e.g., a digital subscriber loop access multiplexer (DSLAM).

Each subscriber line 12-14 consists of a standard twisted two-wire telephone line adapted to voice transmissions. The two wires are generally referred to as the ring AR@ and tip AT@ wires.

A large portion of each subscriber line 12-14 is housed in one or more standard telephone cables 22. The cable 22 carries many subscriber lines 12-14, e.g., more than a dozen, in a closely packed configuration. The close packing creates an electrical environment that changes transmission properties of the individual subscriber lines 12-14.

Electrical measurements for detecting line faults are performed by a measurement unit 40. In various embodiments, the measurement unit 40 includes one or both devices 41 and 43. Each device 41, 43 performs one-ended electrical measurements on selected lines 12-14. In preferred embodiments, the electrical measurements are one-ended. The device 41 performs measurements on tip and ring wires of a selected subscriber line 12-14 in a common mode configuration and produces results useful for detecting split pairs. The device 43 can measure admittances of the tip and ring wires of a selected line 12-14 either separately or together and produces data useful for determining the specific physical line structure. The measurement unit 40 may also house other devices (not shown) for performing other types of electrical measurements, i.e., one-ended or two-ended measurements. The measurement unit 40 couples to the

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switch 15 via a test bus 42.

The devices 41, 43 connect to the switch 15 through the test bus 42 and a standard voice test access 44. The voice test access 44 electrically connects either the device 41 or device 43 to the subscriber lines 12-14 selected for testing. The voice test access 44 generally transmits electrical signals with low frequencies between about 100 Hertz (Hz) and 20 kilo Hz (KHz). But, the test access 44 may transmit signals at higher frequencies, e.g., up to 100 to 300 KHz, in some switches 15.

The measurement unit 40 is controlled by computer 46, which selects the types of measurements performed, the device 41, 43 used, and the subscriber lines 12-14 to test. The computer 46 sends control signals to the measurement unit 40 via a connection 48, e.g., a line, network, or dedicated wire, and receives measurement results from the measurement unit 40 via the same connection 48.

The computer 46 contains a software program for controlling line testing by the measurement unit 40 and for detecting line conditions or faults with results from the measurement unit 40. The software program is stored, in executable form, in a data storage device 49, e.g., a hard drive or random access memory (RAM). The program may also be encoded on a readable storage medium 50, such as an optical or magnetic disk, from which the program can be executed.

To perform a test, the measurement unit 40 signals the voice test access 44 to connect the line 12-14 to be tested to wires of the bus 42 for connecting to internal devices 41, 43. Then, one or both of the internal devices 41, 43 performs electrical measurements on the selected line 12-14. After the measurements are completed, the measurement unit 40 signals the switch 15 to disconnect

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the line 12-14 from the wires of the bus 42.

The computer 46 can classify selected subscriber lines 12-14 prior to fully connecting the lines 12-14 for data services. The range of possible classes to which a line 12-14 can be assigned will depend on the business needs of a TELCO. A simple, but very useful set of classes is "qualified" and "disqualified" to provide data services. Qualification is based on determining, with high certainty, that a selected line 12-14 will support a specified data service. Disqualification is based on determining, with high certainty, that the selected line 12-14 will not support the specified data service.

FIG. 2A shows a first setup 52 for performing one type of one-ended electrical measurements with the device 41. The measurements are used to detect faults such as split pairs in the subscriber lines 12-14 of FIG. 1.

The device 41 has a variable frequency voltage source 54 for driving the tip and ring wires T, R of the subscriber line 12-14 under test. The voltage source drives both wires together, i.e., in a common mode configuration, at a frequency controlled by the measurement unit 40. The tip and ring wires T, R of the line 12-14 under test are connected to the device 41 via the voice test access 44.

The voltage source 54 connects to one side of resistors R_1 and R_2. The second side of resistors R_1 and R_2 connect to the respective tip and ring wires T, R of the subscriber line 12-14 under test. Thus, the voltage source 54 drives the tip and ring wires T, R in common mode through the corresponding resistors R_1 and R_2.

The resistors R_1 and R_2 have equal resistances so that the voltage source 54 induces equal voltages V_1, V_2 between each resistor R_1, R_2 and ground if the currents I_T, I_R therein are also equal. Differences in the input

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impedances Z_T, Z_R of the tip and ring wires T, R make the voltages V_1, V_2 differ in amplitude and/or phase. For example, mutual inductance effects produced by a split pair can make the input impedances Z_T, Z_R unequal.

Voltmeters VM_1 and VM_2 measure amplitudes and phases of voltages V_1 and V_2, respectively. From measurements of the voltmeters VM_1 and VM_2, the computer 46 can obtain the phase difference between V_1 and V_2.

FIG. 2B shows an equivalent circuit 55 for the measurement setup 52 of FIG. 4. In the common mode configuration, the tip and ring wires T, R act as elements of independent circuits 56, 57 that connect the voltage source 54 to a common ground 58. The tip wire T is equivalent to an impedance Z_T in the circuit 56, and the ring wire R is equivalent to an impedance Z_R in the circuit 57.

The input impedances Z_T and Z_R may have different amplitudes and/or phases due to the presence of a fault on either the tip or ring wires T, R. Different values for Z_T and Z_R produce different currents I_T and I_R in the circuits 56 and 57 and different measured voltages V_1 and V_2. The phase of the voltage difference $V_1 - V_2$ is proportional to the phase difference between the input impedances of the tip and ring wires T, R. In the phase of the difference $V_1 - V_2$, termination effects associated with the attached subscriber unit 16 can largely be ignored.

FIG. 2C shows a measuring setup 60 for performing one-ended electrical measurements on a selected subscriber line 12-14 with the device 43 shown in FIG 1. The device 43 measures electrical properties, which can be used to determine the specific physical structure of the lines 12-14 and to determine line conditions and faults as is described below. Some methods for detecting line faults and conditions with the device 43 have been described in

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U.S. Application No. 09/294,563 ('563), filed April 20, 1999. The '563 application is incorporated herein, by reference, in its entirety.

The device 43 is adapted to measure admittances between the tip wire T, ring wire R, and ground G for a subscriber line 12-14 being tested. The tip and ring wires T, R of the line 12-14 being tested couple to driving voltages V_1' and V_2' through known conductances G_t and G_r. The tip and ring wires T, R also connect to voltmeters V_t and V_r. The V_t and V_r voltmeters read the voltage between the tip wire T and ground G and between the ring wire R and ground G, respectively. The readings from the voltmeters V_t and V_r enable the computer 46 to determine three admittances Y_{tg}, Y_{tr}, and Y_{rg} between the pairs tip-ground, tip-ring, and ring-ground, respectively. The device 43 can measure the admittances at preselected frequencies in the range supported by the voice test access 44. The '563 application has described methods for performing such measurements.

Referring to FIG. 3, the computer 46 may compensate for signal distortions introduced by the test bus 42 and/or the voice test access 44. To perform compensation, the computer 46 treats the two lines of the combined bus 42 and test access 44 as a linear two port systems. Then, the currents and voltages I_T', V_T' and I_R', V_R' at the output terminals of the measurement device 40 are related to the currents and voltages I_T, V_T and I_R, V_R on the output terminals of the tip and ring wires T, R by the following 2x2 matrix equations:

$[I_T, V_T] = A(f)\ [I_T', V_T']^t$ and $[I_T, V_T] = A'(f)\ [I_R', V_R']^t$.

The frequency dependent matrices A(f) and A'(f) are determined experimentally for each bus 42 and voice test access 44. Then, the computer 46 calculates the impedances or admittances of the tip and ring wires T, R

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with the currents and voltages I_T, V_T and I_R, V_R obtained from the above equations.

The measurement unit 40 and computer 46 can detect faults such as split pairs, resistive imbalances, metallic faults, load coils, bridged taps, gauge mixtures, and high signal attenuations. Co-pending U.S. Patent Application 09/285,954 ('954), filed April 2, 1999, describes the detection of some of these faults and is incorporated herein by reference in its entirety.

SPLIT PAIRS

Referring again to FIG. 1, close proximity can inductively produce cross talk between the subscriber lines 12-14. Cross talk is frequently caused by large noise or ringing signals on one of the lines 12-14. The large signal inductively produces signals on nearby lines 12-14. To reduce cross talk, the tip and ring wires T, R of each subscriber line 12-14 are either tightly twisted together or kept in close proximity in the cable 22. In this way, stray signals affect both wires of a pair so that induced signals do not impact the difference signal between the tip and ring wires.

Referring to FIG. 4, the tip and ring wires T', R' of a subscriber line 24 are separated spatially in a portion of cable 26. The portion of the subscriber line 24 in which the tip and ring wires T', R' are spatially separated is referred to as a split pair. A split pair T', R' has a high risk of picking up cross talk other lines 28-29 in the same cable 26 or external noise sources such as power lines (not shown).

Split pairs also introduce impedance discontinuities into subscriber lines, because the split pair creates a localized and abrupt impedance variation. Impedance discontinuities can cause signal reflections and high

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signal attenuations for high-speed digital transmissions.

FIG. 5 illustrates one type of split pair, i.e., a split pair caused by a splice error. The splice error occurred when two portions of a subscriber line 32, which are located in two different cables 33, 34, were joined. The splice 35 has joined tip and ring wires T_1, R_2 from two different twisted pair lines 36, 37 in the cable 33 to tip and ring wires T_3, R_3 of a single twisted pair 38 in the adjacent cable 34. The tip and ring wires T_1, R_2 of the portion of the subscriber line 32 are widely separated in a substantial portion of the cable 33. Thus, the tip and ring wires T_1, R_2 form a split pair.

Detection of split pair faults is difficult for several reasons. First, split pairs do not produce easily detected effects such as metallic faults, i.e., broken wires or shorted wires, or impedance imbalances. Second, split pairs produce cross talk that produce intermittent faults depending on the signals on nearby lines, e.g., intermittent ringing signals. The intermittency makes such faults difficult to recognize.

Conventional tests have not been very successful in detecting split pairs. Nevertheless, split pairs can degrade the quality of a subscriber line for high-speed data services.

FIG. 6A and 6B provide graphs 68, 69 of the phase of the voltage difference $V_1 - V_2$ between resistors R_1 and R_2 while testing two exemplary subscriber lines 12-14 with the measurement setup 52 of FIG. 4. The graphs 68, 69 provide frequency sweeps of the phase difference, which show signatures of faults that can interfere with high-speed data services, e.g., ISDN or ADSL.

Referring to FIG. 6A, the graph 68 shows a signature for a resistive imbalance fault on the tested subscriber line 12-14. The signature for a resistive imbalance is a

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pronounced peak in the phase of the voltage difference $V_1 - V_2$. The peak appears in the phase difference between impedances of the tip and ring wires. The peak has a narrow width that is typically not more than a few hundred to about 2 KHz. Typically, the phase has a height of greater than about 5°.

Referring to FIG. 6B, the graph 69 shows a signature for a split pair fault on the tested subscriber line 12-14. The signature is a flat and substantially constant phase for $V_1 - V_2$, i.e., a substantially constant non-zero phase difference between the input impedances Z_T, Z_R of the wires T, R. Typically, the phase has a value of between about .5° and 1.5°. The nonzero and flat phase extends over a region of frequencies having a width of at least 5,000 kilo Hz. The phase of Z_T and Z_R may remain flat, nonzero, and peakless from about 100 Hz to about 20,000 Hz if a split pair is present, i.e., over the frequency range measurable through the voice test access 44, shown in FIG. 1. A nonzero and substantially frequency independent phase difference between the input impedances Z_T, Z_R of the tip and ring wires is a signature for a split pair on the subscriber line 12-14 being tested.

FIG. 7 is a flow chart illustrating a method 70 of detecting a fault in the subscriber lines 12-14 with the system 11 of FIG. 1. The computer 46 selects the subscriber line 12-14 to test for faults (step 72). The measurement unit 40 electrically connects to the selected line 12-14 via the voice test access 44 of the TELCO switch 15 (step 74). The connection produces the measurement setup 52 illustrated in FIGs. 4 and 5.

The measurement unit 40 performs one-ended electrical measurements to determine a signal proportional to the phase difference of the input impedances Z_T, Z_R of the tip

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and ring wires of the selected line 12-14 (step 76). The quantity actually measured is the phase of $V_1 - V_2$, which is proportional to the phase of the difference of the input impedances Z_T, Z_R. The device 41 measures the phase by driving the tip and ring wires in the common mode configuration shown in FIG. 4. The driving frequencies are between about 100 Hz to 20,000 kilo Hz and accessible via the voice test access 44. Such frequencies are very low compared to transmission frequencies of high-speed data services such as ISDN and ADSL.

The computer 46 analyzes the measurements of the phase as a function of frequency to determine whether the phase has a signature for a line fault (step 78). The line faults that produce signatures in the phase include split pairs and resistance imbalances as described above in relation to FIGs. 6B and 6A, respectively. Other signatures are possible, e.g., for other types of faults. If a signature for a line fault is found, the computer 46 identifies that a fault has been detected (step 80). The identification may entail making a reporting act. The reporting act may include making an entry in a file that lists the faults on the subscriber lines 12-14, displaying a warning on an operator's display screen 47 or on a screen of a service technician (not show), or informing a program that allocates subscriber lines 12-14. If no signatures for line faults are found, the computer 46 identifies the absence of the line faults associated with signatures for the selected line 12-14, e.g., by performing a reporting act (step 82).

FIG. 8 is a flow chart illustrating a method 90 for a test that determines whether the subscriber lines 12-14 of FIG. 1 qualify or disqualify for a high-speed data service. To start a test, an operator or the computer 46 selects a subscriber line 12-14 (step 92). The operator

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or computer 46 also selects the type of data service for which the selected subscriber line 12-14 is to be tested (step 94). For example, the types of service may be ISDN or ADSL. After selecting the line 12-14 and service type, the measurement unit 40 performs one-ended electrical measurements to detect preselected types of faults in the selected line 12-14 (step 96). The one-ended measurements include tests according to the method 70 of FIG. 7 to detect split pairs.

The other types of line faults and conditions, which are selected for testing, depend on the types and speeds of data services, the properties of the switch 15, and the type of modem to be used. Frequently, tests check for high signal attenuations, resistive imbalances, and the presence of load coils, metallic faults, or bridged taps, because these conditions and faults can disqualify a line for high-speed data service. But, line qualification tests may also check for capacitive imbalances, and above-threshold noise levels, because these conditions can also affect qualification results. Methods and apparatus for detecting some of these conditions and faults are described in co-pending patent applications.

One such application is U.K. Patent Application No. 9914702.7, titled "Qualifying Telephone Lines for Data Transmission", by Roger Faulkner, filed June 23, 1999, which is incorporated herein by reference, in its entirety. Other such co-pending applications include the above-mentioned '954 and '563 patent applications.

If one of the preselected types of faults or line conditions is detected, the computer 46 reports that the selected subscriber line 12-14 is disqualified for the selected data transmissions (step 98). Otherwise, the computer 46 reports that the selected line 12-14 qualifies for the selected data service (step 100).

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To report the tested line's status, the computer 46 makes an entry in a list stored in the storage device 49. The list identifies the line, data service, and qualification or disqualification status. The computer 46 may also report the line's status by displaying a disqualification or qualification signal on the display screen 47 visible to an operator.

FIG. 9 is a flow chart for a method 101 used by a TELCO to provide a high-speed data service, e.g., ISDN or ADSL, to telephone subscribers. The TELCO programs the computer 46 of FIG. 1 to automatically select individual subscriber lines 12-14 connected to the local switch 15 (step 102). In response to selecting the line 12-14, the voice test access 44 connects the selected line 12-14 to the measurement unit 40 for testing (step 104). The measurement unit 40 connects the selected line 12-14 to the measurement device 41 and may also connect the selected line 12-14 to other internal measurement devices (not shown). The computer 46 and measurement unit 40 determine whether the selected line 12-14 has a split pair and qualifies for the data service according to the methods 70, 90 of FIGs. 7 and 8 (step 106). Next, the computer 46 updates a list recording the identities of lines 12-14 that qualify and of lines 12-14 having split pairs (step 108). The computer 46 waits a preselected time and restarts the testing for another of the lines 12-14 at step 102.

The TELCO regularly checks the list to determine whether any of the lines 12-14 have split pairs (step 110). If a line has a split pair, the TELCO performs a business action based on the presence of the split pair fault (step 112). The business action may include sending a worker to repair or replace the affected line 12-14, designating the affected line 12-14 as unable to transmit

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data, or setting a lower billing rate based on the presence of the fault.

The TELCO also regularly checks the list to determine whether any of the lines 12-14 qualify for the high-speed data service (step 114). In response to finding that one or more of the lines 12-14 qualify, the TELCO performs a business action related to the line's qualification (step 116). For example, the TELCO may offer the high speed data service to subscribers who have the lines 12-14 qualified for the data service and who do not presently subscribe to the data service.

SPECIFIC PHYSICAL STRUCTURE OF SUBSCRIBER LINES

Referring again to FIG. 1, the subscriber lines 12-14 may have widely different physical structures. A line's specific physical structure is described by properties such as line length, gauge or gauges, and content of bridge taps. Interpretations of electrical measurements to obtain line transmission properties such as the signal attenuation are dependent upon the specific physical line structure. Thus, knowing the specific physical structure of a subscriber line aids in predicting how well the line 12-14 will support high speed digital data services, e.g., to predict maximum data speeds.

FIGs. 10A-E illustrate parameters that describe gauge mix parameters through exemplary lines 121-125 in which drawing widths represent wire gauges. The lines 121, 122 have uniform structures described by different wire gauges. The lines 124, 125 have segmented structures in which adjacent segments have different wire gauges, i.e., mixtures of gauges. The gauge composition of these lines 124, 125 is described by segment lengths and segment gauges. The structures are also described by the serial layout of the segments. The line 123 has different tip

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and ring wires T_4, R_4 and is described by the gauges of the T_4 and R_4 wires.

Referring now to FIG. 11, a subscriber line 127 has an extra twisted wire pair 128 spliced onto the line 127. The spliced on wire pair 128 is referred to as a bridged tap. The existence or absence of bridged taps is a parameter that also influences how well the subscriber line 127 will support high-speed digital data services.

In the United States, many subscriber lines have bridged taps because of the way in which telephone lines were laid out in housing subdivisions. Telephone lines were laid out prior to determining the exact positioning of the houses of the subdivisions. The lines ran near planned positions of several houses. When the houses were later built, the builder connected the telephone units to the nearest point on one of the originally laid telephone lines. Unconnected portions of the original lines produced bridged taps.

The bridged tap 128 reflects signals from termination 129. The reflected signals then travel back to the subscriber line 127 and interfere with signals on the subscriber line 127. The most harmful interference occurs when the reflected signal is out of phase with the incoming signal. In such a case, the reflected signal destructively interferes with the incoming signal on the subscriber line 127.

The length of the bridged tap 128 determines the phase difference between the original and reflected signals. For high-speed digital signals whose frequencies extend to about 1 mega Hertz (MHz), e.g., ADSL signals, a substantial cancellation can occur if the bridged tap 128 has a length between about 200 to 700 feet. In the United States, the bridged taps left over from the construction of many housing subdivisions have lengths in this range.

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Thus, the ability to detect and remove the bridged tap 128 is useful to TELCO's that want to offer high-speed digital data services to their subscribers.

FIGs. 12A-12E illustrate structure parameters that describe bridged taps 130, 134 through exemplary subscriber lines 135-139. The lines 135, 136 have bridged taps 130, 131 described by different physical lengths. The lines 137-138 have bridged taps 132, 133 described by different locations along the lines 137, 138. The line 139 has a bridged tap 134, which is at least partially described by its location along a particular segment of the line 139. Finally, the lines 136, 139 have bridged taps 131, 134 described by different gauges.

To determine the specific physical structures of unknown subscriber lines, a reference set of model lines may be employed. A reference set is an ensemble of model lines with different and known specific physical structures. To determine the specific physical structure of an unknown subscriber line, measured properties of the unknown line are compared to the same properties in model lines. If a match is found, the unknown line has the same specific physical structure as the matching model line.

Reference data on the specific physical structures of the model lines may be compiled in either a reference data file or a set of reference equations. Both the reference data file and the set of reference equations index the individual model lines by values of a preselected set of measurable electrical properties. In some embodiments, the preselected electrical properties are the frequency-dependent admittances measurable with the device 43 of FIG. 2C.

The content of model lines in the reference set may be tailored to the expected structures of the unknown subscriber lines. For example, if the unknown lines do

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not have bridged taps, the reference set might not have model lines with bridged taps. On the other hand, if the unknown lines may have bridged taps, the reference set includes some model lines with bridged taps. Knowledge of the practices used to lay out the subscriber lines under test can help to determine the best content of model lines for the reference set. For different subscriber line populations, reference sets can be selected empirically or based on human knowledge.

Typically, the reference set includes model lines having uniformly varying values of the parameters described in relation to FIGs. 10A-10E and 12A-12E. The model lines have a distribution of lengths and may include one, two, or three segments with zero, one, or two bridged taps, and a distribution of subscriber termination loads. The segments and bridged taps can have varying lengths, locations, and gauges.

FIG. 13 is a flow chart for a method 140 of determining the specific physical line structure of the subscriber lines 12-14 of FIG. 1 from a reference set of model lines. To start, an operator or the computer 46 selects a subscriber line (ssl) to test (step 142). The computer 46 directs the measuring unit 40 to perform preselected one-ended electrical measurements on the selected subscriber line over a range of frequencies (step 144).

In one embodiment, the electrical measurements are one-ended and performed with the device 43, shown in FIG. 2C. During the measurements, the voltage source 54 drives the tip and/or ring wires of the selected subscriber line 12-14 with voltage sources V_1', V_2'. The driving frequency is swept over a range, e.g., from about 100 Hertz to about 20,000 to 40,000 Hertz, and one or more of the admittances Y_{tg}, Y_{tr}, Y_{rg} are measured for various driving frequencies.

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The measurements provide complex input admittances, i.e., amplitudes and phases for a preselected set of frequencies "f".

After performing the measurements, the computer 46 searches for a "best" match between model lines belonging to the reference set and the selected subscriber line (step 146). The search for matches involves comparing preselected electrical properties of the selected subscriber line to the same properties for the model lines. For the selected subscriber line, the values of the preselected electrical properties are obtained from the one-ended electrical measurements. For the model lines, the values of the same electrical properties are either looked up from a file in the data storage device 49 or calculated from a set of reference equations. The comparison determines which model line "best" matches the selected subscriber line.

The computer 46 identifies a specific physical line structure for the selected subscriber line 12-14 has the same form as the specific physical line structure of the "best" matching model line (step 148). Identifying the specific physical line structure may include reporting the structure, e.g., displaying values of parameters for the specific physical structure to a operator, writing the values to a file, or providing the values to a software application. For example, the software application may use the match information to qualify or disqualify the selected line 12-14. The parameters may provide gauge mixtures and tap locations and positions.

For the model lines, the specific physical structures are either stored in the same file listing the electrical properties of the model lines or determined from the reference equations. Actual values of the electrical properties and structure parameters of the model lines are

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obtained prior to testing the subscriber line by analytic calculations or experimentation.

In a preferred embodiment, the computer 46 finds the "best" matching model line by calculating an error function for each model line (ml). The error function has one of two forms E or E' given by:

$E = \Sigma_f W(f)|M_{ml}(f) - M_{sl}(f)|$ and $E' = \Sigma_f W(f)|M_{ml}(f) - M_{sl}(f)|^{2Q}$.

$M_{ml}(f)$ and $M_{ssl}(f)$ are the values of the preselected frequency-dependent electrical properties of the model line (ml) and the selected subscriber line (ssl), respectively. Q and W(f) define the form of the error functions, i.e., E or E'. Q is a fixed integer, e.g., 1 or 2. W(f) is positive definite weight function, e.g., a function of frequency "f" or a constant.

In some embodiments, the preselected electrical properties $M_{ml}(f)$, $M_{ssl}(f)$ are the phases of one or more complex admittances of the lines ssl, ml. Various embodiments employ either the phase of the tip-to-ground admittance Y_{tg}, the phase of the ring-to-ground admittance Y_{rg}, and/or the phase of the tip-to-ring admittance Y_{tr}. If the tip-to-ground or ring-to-ground admittances Y_{tg}, Y_{rg} are used, many termination effects due to the subscriber units 16-18 of FIG. 1 are not seen. The phase of these admittances is often small, e.g., 4° or less, and approximately equals the ratio of the imaginary to real parts of the admittance. For such a case and Q = 1, the error function E' is:

$$E' = \Sigma_f [\ \mathrm{Im(admittance)}_{ml}/\mathrm{Re(admittance)}_{ml} - \mathrm{Im(admittance)}_{ssl}/\mathrm{Re(admittance)}_{ssl}\ ]^2.$$

In another embodiment, the preselected electrical properties $M_{ml}(f)$, $M_{ssl}(f)$ are the full complex admittances of the lines ssl, ml, i.e., Y_{tg}, Y_{rg}, and/or Y_{tr}. Using the

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complex admittances themselves can reduce computational times.

Finally, in some embodiments, the best match to the selected subscriber line 12-14 may include a several different model lines, e.g., model lines generating errors with a below threshold value. In these embodiments, the computer 46 identifies the selected subscriber line 12-14 as having one or more common features of all of the "best matching" lines. For example, the computer 46 may identify the specific physical structure of the selected subscriber line 12-14 as having a bridged tap if all of the best matching model lines have a bridged tap. Then, the computer 46 may use the presence of a bridged tap in combination with other measurements to qualify or disqualify the line 12-14.

FIG. 14 illustrates a method 150 of determining "best" matches by using the above-described phases. The computer 46 determines the length of the selected subscriber line using low frequency measurements for line capacitance performed by the measurement unit 40 and device 43 (step 152). Next, the computer 46 selects a model line having the same length as the selected subscriber line (step 154).

The computer 46 restricts comparisons to model lines with the same length as the subscriber line, because physical line length affects the values of the phases of admittances. Limiting comparisons to this subset of the reference set eliminates false matches with model lines whose lengths differ from the length of the selected subscriber line.

The computer 46 calculates the error function E', based on the phase of preselected admittances, for the selected model line (step 155). The computer 46 checks whether other model lines remain with the same length

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(step 156). If other lines remain, the computer 46 repeats the determination of E' for another selected model line (157). If no lines remain, the computer 46 reports the model line having the smallest value for the error function E' as the "best" match to the selected subscriber line (step 158).

Since the reference set may contain as many as 10,000 to 100,000 model lines, the method 150 may search the reference set hierarchically to reduce the total number of searches. In a hierarchical scheme, a first search divides the reference set into non-overlapping groups of model lines. Each group has a large number of lines with similar specific physical structures and defines one model line as a representative of the group. The first search uses the method 150 to determine a "best" match between the selected subscriber line and one of the representative model lines. A second search uses the method 150 on the model lines of the group associated with the best matching representative model line found from the first search.

FIG. 15 is a flow chart illustrating a method 160 of qualifying subscriber lines, e.g., lines 12-14 of FIG. 1, for a high-speed data service, e.g., ISDN or ADSL. After selecting a subscriber line to test, the computer 46 searches a reference set of model lines for a "best" match to the selected subscriber line by using the methods 140, 150 of FIGs. 13 and 14 (step 162). The computer 46 identifies the selected subscriber line as having a bridged tap or mixture of gauges in response to the "best" match model line having a bridged tap or mixture of gauges, respectively (step 163). The computer 46 qualifies or disqualifies the selected subscriber line for the data service, at least in part, based upon whether the subscriber line has a bridged tap or mixture of gauges (step 164).

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In some embodiments, the computer 46 uses the signal attenuation to qualify or disqualify the selected subscriber line according to a method described in co-pending U.S. Application No. 08/294,563 ('563). In those embodiments, the computer 46 calculates the signal attenuation by the methods described in the '563 application. Then, the computer 46 adjusts the calculated value of the signal attenuation up or down depending on a quality factor. The quality factor depends on the specific physical structure of the line, e.g., upon whether a bridged tap and/or a mixture of gauges is absent or present in the subscriber line.

According to the value of the quality factor, the computer 46 adjusts a calculated signal attenuation up or down by preselected amounts. For example, the attenuation may be decreased, unchanged, and increased in response to the quality factor being good, average, and poor, respectively. Then, the computer uses the adjusted signal attenuation to determine to qualify or disqualify the subscriber line for the data service according to methods described in the '563 application.

In other embodiments, the computer 46 uses some specific physical line structures as disqualifiers. For example, if the above-described methods lead to the detection of a bridged tap, the computer 46 may disqualify the line for the data service.

FIG. 16 is a flow chart illustrating a business method 165, which a TELCO uses to provide a high-speed data service to subscribers. The TELCO determines which subscriber lines 12-14 of FIG. 1 are qualified and/or disqualified for the data service according to the method 160 of FIG. 15 (step 166).

Using the method 160, the computer 46 determines whether line structures, e.g., bridged taps and/or

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selected mixtures of gauges, are present. The specific physical structure is then used to adjust predictions of electrical properties of the subscriber line, e.g., a signal attenuation. If the adjusted values of the electrical properties are outside of thresholds for the data service the line is disqualified.

Among subscribers with qualified lines 12-14, the TELCO determines which subscribers having qualified lines do not subscribe to the data service (step 167). The TELCO offers the data service to subscribers having qualified lines and not presently subscribing to the service (step 168).

In response to finding subscribers with disqualified lines 12-14, the TELCO repairs or replaces those lines 12-14 (step 169).

STACKED BRIDGED TAP DETECTION

Referring again to FIG. 1, tests for bridged taps preferably use one-ended electrical measurements that are performed on subscriber lines 12-14 via the "standard" voice test access 44. The voice test access 44 acts as a low pass filter, which screens out frequencies above 20 to 100 KHz. Thus, electrical measurements are generally restricted to low frequencies between about 20 Hz and 100 KHz.

Bridged taps manifest their presence by peaks in the signal attenuation at high frequencies, e.g., between about 200 KHz and 1,000 KHz. Predicting features of the high- frequency signal attenuation from the low-energy measurements, which are available through the voice test access 44, is difficult and error prone. Present methods falsely predict the presence or absence of bridged taps in about 40% of the cases. False predictions are costly to subscribers and TELCO's, because they can result in lost

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opportunities for high-speed data services and can also result in investments in transmission equipment that lines do not support.

The accuracy of tests for line conditions and faults, e.g., bridged taps, can be improved with stacked generalization methods that use multiple layers of classifiers. The classifiers determine values of auxiliary variables, which are the labels they assign to classify subscriber lines 12-14. Auxiliary variables are generated as outputs of classifiers. The auxiliary variables are thus, related to electrical measurements on the lines 12-14 indirectly through probabilistic relations embodied in the classifiers. The classifiers of the stack may be decision trees, neural networks, case-based reasoners, or statistically based classifiers. The old electrical properties and new auxiliary variables can be combined in classifiers that provide strong correlations between values of these quantities and the presence or absence of line faults and conditions, such as bridged taps and gauge mixtures.

FIG. 17 is a flow chart illustrating a method 170 for using stacked classifiers to detect selected line conditions or faults from electrical measurements made with the system 11 of FIG. 1. The system 11 preferably performs one-ended electrical measurements on a selected subscriber line 12-14 using either setup 52 or setup 60, shown in FIGs. 2A-2C, 3 (step 172). To these measurements, the computer 46 applies a set of rules that define a preselected set of derived electrical properties for the selected line 12-14 (step 173). Algebraic relations relate the derived properties to the measurements. The measured and derived electrical properties are listed in Appendix A.

The measured and derived properties together form the

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input properties for the stack of classifiers. These input properties may include a preliminary value of the signal attenuation, the line length, line impedances, and ratios of line impedances. The selection of the input line properties for the stack can be changed to accommodate different expected compositions of the subscriber lines 12-14 being tested.

In each layer U, V of classifiers, shown in FIG. 17, the computer 46 determines values of one or more auxiliary variables for the selected line 12-14. The auxiliary variables may be logic-type variables indicating that the line 12-14 is labeled by a characteristic. The auxiliary variables may also be probability-type variables each indicating the likelihood that the line 12-14 is labeled by one of a plurality of characteristics.

In the first layer U of the stack, the computer 46 applies a first classifier to input electrical measurements and properties to determine a first auxiliary variable (step 175). The first auxiliary variable characterizes the line 12-14 with a label "nominal" or a label "non-nominal".

In a nominal line, low frequency properties provide a good prediction of the signal attenuation at the high frequencies where bridged taps strongly affect attenuation. Thus, knowing a value of an auxiliary variable that labels a line as nominal or non-nominal can improve the accuracy of predictions about the presence of line faults like bridged taps.

Also in the first layer U, the computer 46 applies one or more second classifiers to the input electrical properties to determine one or more other auxiliary variables (step 176). These auxiliary variables provide a preliminary prediction of whether the selected line 12-14 is qualified or disqualified for one or more high-speed

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data services. In some embodiments, values of the auxiliary variables, found at step 176, indicate whether the subscriber line 12-14 is qualified for ISDN or ADSL data services or neither.

Disqualification for high-speed data service correlates with presence of a bridged tap, because a bridged tap lowers a line's capability to carry high-frequency signals. Thus, knowing a value of an auxiliary variable that preliminarily labels a line as qualified or disqualified for data transmissions can improve the accuracy of predictions about the presence or absence of bridged taps.

Steps 175 and 176 may be performed in parallel or sequentially. If these steps 175 and 176 are sequential, the value of the auxiliary variable output by the earlier step may be used in the later step. If step 175 is earlier, the classifier of step 176 may use the auxiliary variable labeling the line 12-14 as nominal or non-nominal, as an input. If step 176 is earlier, the classifier of step 175 may use the auxiliary variables providing a preliminary qualification or disqualification for data transmissions as inputs.

At the second layer V of the stack, the computer 46 applies a classifier to the auxiliary variables from steps 175 and 176 and the electrical measurements and properties from steps 172 and 173. This classifier determines whether the selected subscriber line 12-14 has a preselected type of line fault or condition (step 177). For example, the fault or condition may be existence of a bridged tap or a gauge mixture.

The layered stack U, V can predict the presence or absence of bridged taps with a substantially increased accuracy. The two-layered stack of FIG. 17 can predict the presence of bridged taps with an accuracy of between

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about 75% and 85% and the absence of bridged taps with an accuracy of greater than about 97%.

In steps 175, 176, and 177, classifiers analyze input data to determine the values of output data. Henceforth, the input data, which includes one-ended measurements, properties derived from one-ended measurements, and/or auxiliary variables, are referred to as line features. The output data, which are values of auxiliary variables, are referred to as classifying labels.

Their line features and labels can describe the classifiers of steps 175, 176, and 177. The classifier in step 175 uses the selected measured and derived electrical properties of the selected line 12-14 as features to form classes with labels "nominal" and "non-nominal". The classifier of step 176 uses the same features to form classes with labels "ISDN qualified", "ADSL qualified", or "data service disqualified" in one embodiment. The classifier of step 177 uses the same features and values of the characterizing labels from steps 175, 176 to form classes with labels "bridged tap present" and "bridged tap absent".

The label "nominal" describes a type of signal attenuation over a range that includes both low measurement frequencies and high data service frequencies. For a nominal line, the difference between actual and predicted signal attenuations AA(f) and PA(f) has a simple dependence on frequency "f". The actual signal attenuation AA is the attenuation of the line determined from direct double-ended electrical measurements. The predicted signal attenuation PA is the attenuation obtained from one-ended electrical measurements, e.g., using the system 11 of FIG. 1.

The predicted signal attenuation PA(f) may be obtained from a subscriber line's capacitance, e.g., the

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capacitance C^{tg}_{30Hz} between tip wire and ground measured at 30 Hz. One form for the predicted signal attenuation PA(f) is:

$$PA(f) = K(f)C^{tg}_{30Hz}.$$

In this formula, K(f) = -.1729, -.2074, -.2395, -.2627, and -.2881 dB/nano-Farads for respective frequencies f equal to 100, 200, 300, 400, and 500 KHz.

Another form for the predicted attenuation PA(f) is described in co-pending U.K. Patent Application 9914702.7.

For a nominal line, the difference, DFF(f), between the actual and the predicted signal attenuations AA(f), PA(f) has one of the following forms:

1) DFF(f) < 3.5 dB for 100 KHz < f < 500 KHz;

2) 3.5 dB $\leq$ DFF(f) < 10.0 dB for 100 KHz < f < 500 KHz; or

3) DFF(f) $\geq$ 10.0 dB for 100 KHz < f < 500 KHz.

If the frequency dependent difference DFF(f), i.e., |AA(f)-PA(f)|, does not have form 1, 2, or 3, the line 12-14 is classified as a non-nominal line. Thus, a direct determination of whether a particular line 12-14 is nominal requires both one-ended and two-ended measurements to obtain both PA(f) and AA(f).

FIG. 18A shows predicted and actual attenuations of exemplary nominal lines A, B, and C. For the line A, predicted and actual attenuations PA_A and AA_A differ by less than 3.5 dB for the entire frequency range between 100 and 500 KHz. The line A has a DFF(f) of form 1. For the line B, predicted and actual attenuations PA_B, AA_B differ by between 4 and 9 dB over the 100 KHz to 500 KHz frequency range. The line B has a DFF(f) of form 2. For the line C, predicted and actual attenuations PA_C, AA_C differ by between more than 10.0 dB over the 100 KHz to 500 KHz frequency range. The line C has a DFF(f) of form

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3.

FIG. 18B shows predicted and actual attenuations of exemplary non-nominal lines D and E. For the line D, predicted and actual signal attenuations PA_D, AA_D differ by about 8 dB at 200 and 400 KHz and are equal at 150 and 300 KHz. This form for PA_D and AA_D does not correspond to a DFF(f) of form 1, 2, or 3. For the line E, predicted and actual signal attenuations PA_E, AA_E differ by less than 3.5 dB at frequencies between 100 and 200 KHz and by more than 8 dB at frequencies between 400 and 500 KHz. This form for PA_E and AA_E also does not correspond to a DFF(f) of form 1, 2, or 3.

In the non-nominal lines D and E wide fluctuations occur in DFF(f). These fluctuations make a constant shift of the predicted attenuation PA(f) a poor approximation to the actual attenuation AA(f) over the whole range that includes both high and low frequencies.

FIG. 18C shows predicted and actual signal attenuations PA_F, AA_F for another nominal subscriber line F. A shifted predicted attenuation SPA_F, which has been obtained by shifting the predicted attenuation PA_F by a constant, is also shown. For the nominal line F, the shifted predicted attenuation SPA_F provides a better approximation to the actual attenuation AA_F that the predicted attenuation PA_F over the entire range between 100 KHz and 500 KHz.

The actual and predicted signal attenuations AA(f), PA(f) of nominal lines are approximately related by a constant shift over a wide frequency range. The wide frequency range includes both low measurement frequencies and high frequencies where effects of bridged taps are directly observable.

In step 176 of FIG. 17, the labels ISDN qualified, ADSL qualified, and data service disqualified are defined

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by the value of the actual signal attenuation at 100 KHz and 300 KHz. High-speed data qualified and disqualified lines satisfy:

Class Label	100 KHz	300 KHz
ADSL qualified	attenuation > -47dB	attenuation > -40
ISDN qualified	attenuation > -47dB	attenuation ≤ -40
Disqualified	attenuation ≤ -47dB	attenuation ≤ -40

Thus, qualification or disqualification of a line 12-14 for ADSL and ISDN are defined by the value of the actual signal attenuation at two high frequencies, i.e., 100 KHz and 300 KHz.

FIG. 19 illustrates a decision tree 180 that determines a classifying label, e.g., an auxiliary variable, generated in steps 175-177 of FIG. 17. A separate classifier, e.g., a decision tree, is used to determine each such label.

The decision tree 180 has a hierarchical arrangement of branching tests 1, 1.1-1.2; 1.1.1-2.2.2,..., which are grouped into descending levels 1, 2, 3.... Each test assigns feature data received from a higher level to disjoint subsets in the next lower level. The subsets of the lower level are located at ends of arrows starting at the test. For example, test 1.1 assigns feature data to subsets 1.1 and 1.2, which are located at the ends of arrows 6 and 7, see FIG. 20. At the lower level, another set of tests can act on the feature data.

FIG. 20 illustrates how the tests 1, 1.1, 1.2,... of the various levels of the decision tree 180 of FIG. 19 act on a set of feature data associated with the subscriber lines 12-14. Each successive test partitions the set, i.e., by using values of the selected features, into increasingly disjoint output subsets. For example, test 1

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partitions the initial feature data into subset 1 and subset 2. The distal end of each path through the decision tree 180 assigns a subscriber line to a final subset in which the lines are primarily associated with one value of the classifying label of the tree 180. Some decision trees 180 determine a probability that the subscriber line 12-14 has the value of the label of the final subset to which it is assigned.

FIG. 21 is a flow chart for a method 190 of creating decision trees for use as the classifiers in steps 175, 176, and 177 of FIG. 17. The method 190 uses machine learning methods.

To employ machine learning, a training set of subscriber line data is created (step 192). The content the training set includes model lines with different values of the labels used by the decision tree to classify lines. If the decision tree classifies lines with the label "bridged tap present" and "bridged tap absent", then some of the lines of the training sets will have bridged taps and some of the lines will not have bridged taps. Similarly, in a stack of trees that classifies lines with a particular label, each tree therein is constructed from a training set having lines with different values of the particular label.

For each line of the training set, a computer and/or operator determines the values of a set of potential features and the classifying labels (194).

The potential features include one-ended measured and derived electrical properties that may be used in the tests of the decision tree. The potential electrical properties of one embodiment are listed in Appendix A. The potential features also include values of any auxiliary variables that may be used in the tests of the decision tree. For example, a decision tree used in step

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177 of FIG. 17 would also include, as potential features, auxiliary variables determining whether a line is nominal and preliminarily qualified for preselected data services.

The classifying labels are the values of the auxiliary variables output by the decision tree. The values of these output auxiliary variables may, for example, include a determination of whether a line is nominal, qualified, or has a bridged tap.

Determinations of values of the classifying labels for the lines of the training set may use both one-ended and two-ended electrical measurements. For example, to classify a line of the training set as nominal or non-nominal a two-ended measurement of the actual attenuation and a one-ended measurement of the predicted attenuation are needed. Similarly, to determine the classifying label associated with qualification for data services, two-ended measurements of the actual attenuation are used. The two-ended measurements are not, however, used as inputs in the construction of decision trees.

From the values of the potential features and classifying labels of each line in the training set, the computer 46 recursively determines the branching tests of the decision tree (step 196).

FIG. 22 is a flow chart for a method 200 of determining the branching tests of the decision tree 180 shown in FIGs. 19-20. For each potential feature, the computer 46 constructs a test and partitions the training set into groups of disjoint subsets (step 202). The test associated with a feature assigns each line of the training set to subsets according to a value of that feature for the line.

The computer 46 evaluates gain ratio criteria for the partitioning of the training set produced by each

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potential feature (step 204). The gain ratio criteria measures increases in consistency of line membership for different values of the classification label in each subset. The computer 46 uses the gain ratio criteria to find a best test and defines test 1 of the decision tree 180 to be the best test (step 206).

The computer loops back to perform steps 202, 204, and 206 for each subset produced by test 1 to determine the tests of level 2 of the decision tree 180 (loop 208). In these determinations, the subsets produced by the best test of level 1 become training sets for finding the tests of level 2. After performing steps 202, 204, and 206 for the subsets 1 and 2, the computer 46 has determined the tests 1.1 and 1.2 of the level 2 (loop 208). The computer 46 performs loop 208 either until further branches produce line classification errors below a preselected threshold or until no features remain.

Several methods exist for defining the best branching tests at each level of the decision tree 180 of FIG. 19. The C4.5 method defines best tests as tests producing the highest values of the gain ratio criteria. The C4.5* method randomly picks the best tests from the tests whose values of the gain ratio criteria are within a preselected selection percentage of the highest value.

The C4.5* algorithm predicts probabilities that a line with features "d" will be partitioned into each final subset of the decision tree. The probability that the line will be in the majority final subset L is:

$$P_L(d) = 1 - (\Sigma_{(j \text{ not in } L)} N_j + 1) / (\Sigma_{(i \text{ in } L)} N_i + 2).$$

Here, N_i is the number of lines in subset "i". The probability that the line will be in a subset "i" is:

$$P_i(d) = [1 - P_L(d)] (N_i / \Sigma_{(j \text{ in } L)} N_j).$$

In embodiments using the C4.5* algorithm, the above-

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described probabilities are the auxiliary variables used as features in the steps 175-177 of FIG. 17.

Various embodiments combine the methods of detecting line faults (70, 90), determining lines structures (140, 160), and stacking fault detection (170), shown in FIGs. 7, 8, 13, 15, 17. By combining the above-mentioned methods, these embodiments can better classify subscriber lines according to a variety of criteria. These criteria include presence of line conditions and faults, line speed, and qualification status.

Other embodiments are within the scope of the following claims.

What is claimed is:

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30Hz Raw Measurements:
Ytr(30) - Admittance tip-to-ring measured at 30Hz
Ytg(30) - Admittance tip-to-ground measured at 30Hz
Yrg(30) - Admittance ring-to-ground measured at 30Hz

30Hz Derived Measurements:
30Gtr - Conductance tip-to-ring measured at 30Hz = real(Ytr(30))
30Str - Susceptance tip-to-ring measured at 30Hz = imag(Ytr(30))
30Gtg - Conductance tip-to-ground measured at 30Hz = real(Ytg(30))
30Stg - Susceptance tip-to-ground measured at 30Hz = imag(Yt(30))
30Ctr - Capacitance tip-to-ring measured at 30Hz = Str(30)/(2*pi*30)
30Ctg - Capacitance tip-to-ground measured at 30Hz = St(30)/(2*pi*30)
Lmeas - Length in kft measured at 30Hz = 30Ctg/17.47

150Hz-20KHz Raw Measurements:
Ytr(f) - Admittance tip-to-ring where f=150Hz,600Hz,1050Hz,1500Hz....19950Hz
Ytg(f) - Admittance tip-to-ground where f=150Hz,600Hz,1050Hz,1500Hz....19950Hz
Yrg(f) - Admittance ring-to-ground where f=150Hz,600Hz,1050Hz,1500Hz....19950Hz

150Hz-20KHz Derived Measurements:
150Gtr - Conductance tip-to-ring measured at 150Hz = real(Ytr(150))
600Gtr - Conductance tip-to-ring measured at 600Hz = real(Ytr(600))

19950Gtr - Conductance tip-to-ring measured at 19950Hz = real(Ytr(19950))

150Str - Susceptance tip-to-ring measured at 150Hz = imag(Ytr(150))
600Str - Susceptance tip-to-ring measured at 600Hz = imag(Ytr(600))

19950Str - Susceptance tip-to-ring measured at 19950Hz = imag(Ytg(19950))

150Gtg - Conductance tip-to-ground measured at 150Hz = real(Ytg(150))
600Gtg - Conductance tip-to- ground measured at 600Hz = real(Ytg(600))

19950Gtg - Conductance tip-to- ground measured at 19950Hz = real(Ytg(19950))

150Stg - Susceptance tip-to- ground measured at 150Hz = imag(Ytg(150))
600Stg - Susceptance tip-to- ground measured at 600Hz = imag(Ytg(600))

19950Stg - Susceptance tip-to- ground measured at 19950Hz = imag(Ytg(19950))

150Ctr - Capacitance tip-to-ring measured at 150Hz = 150Str/(2*pi*150)
600Ctr - Capacitance tip-to-ring measured at 600Hz = 600Str/(2*pi*600)

19950Ctr - Capacitance tip-to-ring measured at 19950Hz = 19950Str/(2*pi*19950)

150Ctg - Capacitance tip-to-ground measured at 150Hz = 150Stg/(2*pi*150)
600Ctg - Capacitance tip-to-ground measured at 600Hz = 600Stg/(2*pi*600)

19950Ctg - Capacitance tip-to-ground measured at 19950Hz = 19950Stg/(2*pi*19950)

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150Hz-20KHz Secondary Derived Measurements:

C30/C4K - Ratio of tip-to-ground Capacitance at 30Hz to 4200Hz
C4K/C10K - Ratio of tip-to-ground Capacitance at 4200Hz to 10050Hz
Cslope - Tip-to-ground Capacitance ratio slope = (C4K/C10K)/(C30/C4K)
C30-C4K - Difference in tip-to-ground Capacitance at 30Hz and 4200Hz
C4K-C10K - Difference in tip-to-ground Capacitance at 4200Hz and 10050Hz
Cdelta - Tip-to-ground Capacitance difference delta = (C4K-C10K)/(C30-C4K)

G4K/G30 - Ratio of tip-to-ground Conductance at 4200Hz to 30Hz
G10K/G4K - Ratio of tip-to-ground Conductance at 10050Hz to 4200Hz
Gslope - Tip-to-ground Conductance ratio slope = (G10K/G4K)/(G4K/G30)
G4K-G30 - Difference in tip-to-ground Conductance at 30Hz and 4200Hz
G10K-G4K - Difference in tip-to-ground Conductance at 4200Hz and 10050Hz
Gdelta - Tip-to-ground Conductance difference delta = (G10K-G4K)/(G4K-G30)

C30/G30 - Ratio of Tip-to-ground Capacitance to Conductance at 30Hz
C30/G4K - Ratio of Tip-to-ground Capacitance at 30Hz to Conductance at 4200Hz
C4K/G4K - Ration of Tip-to-ground Capacitance to Conductance at 4200Hz

Gtr_dmax - Maximum positive slope of Gtr(f) = max(derivative(Gtr(f)/df))
Gtr_fmax - Frequency at which Gtr_dmax occurs
Gtr_dmin - Maximum negative slope of Gtr(f) = min(derivative(Gtr(f)/df))
Gtr_fmin - Frequency at which Gtr_dmin occurs
Gtr_fpk - Frequency of first peak (local maxima)in Gtr(f)
Gtr_fval - Frequency of first valley(local minima)in Gtr(f)
Gtr_d_delta - Gtr Max/Min Derivative difference = Gtr_dmax-Gtr_dmin
Gtr_pk_delta - Gtr peak/valley frequency difference = Gtr_fval-Gtr_fpk
Gtr_pk - Value of Gtr(f) at frequency Gtr_fpk
Gtr_val - Value of Gtr(f) at frequency Gtr_fval
Gtr_delta - Gtr peak/valley difference = Gtr_pk-Gtr_val

Gtg_dmax - Maximum positive slope of Gtg(f) = max(derivative(Gtg(f)/df))
Gtg_fmax - Frequency at which Gtg_dmax occurs
Gtg_dmin - Maximum negative slope of Gtg(f) = min(derivative(Gtg(f)/df))
Gtg_fmin - Frequency at which Gtg_dmin occurs
Gtg_d_delta - Gtg Max/Min Derivative difference = Gtg_dmax-Gtg_dmin

Ctr_dmax - Maximum positive slope of Ctr(f) = max(derivative(Ctr(f)/df))
Ctr_fmax - Frequency at which Ctr_dmax occurs
Ctr_dmin - Maximum negative slope of Ctr(f) = min(derivative(Ctr(f)/df))
Ctr_fmin - Frequency at which Ctr_dmin occurs
Ctr_fpk - Frequency of first peak (local maxima)in Ctr(f)
Ctr_fval - Frequency of first valley(local minima)in Ctr(f)
Ctr_d_delta - Ctr Max/Min Derivative difference = Ctr_dmax-Ctr_dmin
Ctr_pk_delta - Ctr peak/valley frequency difference = Ctr_fval-Ctr_fpk
Ctr_val - Value of Ctr(f) at frequency Ctr_fval

Ctg_dmax - Maximum positive slope of Ctg(f) = max(derivative(Ctg(f)/df))
Ctg_fmax - Frequency at which Ctg_dmax occurs
Ctg_dmin - Maximum negative slope of Ctg(f) = min(derivative(Ctg(f)/df))
Ctg_fmin - Frequency at which Ctg_dmin occurs
Ctg_d_delta - Ctg Max/Min Derivative difference = Ctg_dmax-Ctg_dmin

Str_dmax - Maximum positive slope of Str(f) = max(derivative(Str(f)/df))
Str_fmax - Frequency at which Str_dmax occurs
Str_dmin - Maximum negative slope of Str(f) = min(derivative(Str(f)/df))
Str_fmin - Frequency at which Str_dmin occurs

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150Hz-20KHz Secondary Derived Measurements:

Str_fpk - Frequency of first peak (local maxima)in Str(f)
Str_fval - Frequency of first valley(local minima)in Str(f)
Str_d_delta - Str Max/Min Derivative difference = Str_dmax-Str_dmin
Str_pk_delta - Str peak/valley frequency difference = Str_fval-Str_fpk
Str_pk - Value of Str(f) at frequency Str_fpk
Str_val - Value of Str(f) at frequency Str_fval
Str_delta - Str peak/valley difference = Str_pk-Str_val

Stg_dmax - Maximum positive slope of Stg(f) = max(derivative(Stg(f)/df))
Stg_fmax - Frequency at which Stg_dmax occurs
Stg_dmin - Maximum negative slope of Stg(f) = min(derivative(Stg(f)/df))
Stg_fmin - Frequency at which Stg_dmin occurs
Stg_fpk - Frequency of first peak (local maxima)in Stg(f)
Stg_fval - Frequency of first valley(local minima)in Stg(f)
Stg_d_delta - Stg Max/Min Derivative difference = Stg_dmax-Stg_dmin
Stg_pk_delta - Stg peak/valley frequency difference = Stg_fval-Stg_fpk

Gtg20k/Gtg8k - Ratio of Gtg at 19950Hz and 8250Hz
Gtg20k/Gtg4k - Ratio of Gtg at 19950Hz and 4200Hz
Cgt30/Cgt20k - Ratio of Ctg at 30Hz and 19950Hz
Cgt30/Cgt8k - Ratio of Ctg at 30Hz and 8250Hz

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What is claimed is:

1. A method of determining a physical structure of a subscriber line, comprising:

searching a reference set for a match between the subscriber line and a model line of the reference set, the match being based on electrical properties of the lines; and

identifying that the subscriber line has a specific physical structure in response to finding a match with one of the model lines that has the specific physical structure.

2. The method of claim 1, further comprising:

performing electrical measurements to determine the electrical properties, the electrical measurements being one-ended measurements.

3. The method of claim 2, wherein the act of searching comprises:

evaluating an error function for each model line to determine quality of the match between values of the electrical properties of the model and subscriber lines.

4. The method of claim 2, wherein the one-ended measurements determine one of a tip-to-ring admittance, a tip-to-ground admittance, and a ring-to-ground admittance.

5. The method of claim 4, wherein the electrical properties include a quantity representative of a phase of an impedance of the subscriber line.

6. The method of claim 4, wherein the act of

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performing includes transmitting a voltage signal to the subscriber line through a test access of a switch or a DSLAM device.

7. The method of claim 2, wherein the act of identifying indicates that the subscriber line has one or more bridged taps in response to the matching model line having one or more bridged taps.

8. The method of claim 2, wherein the act of identifying indicates that the subscriber line has a mixture of gauges in response to the matching model having a mixture of gauges.

9. The method of claim 2, wherein the act of searching for comprises:

looking up values of the electrical properties of the model lines in a data storage device.

10. The method of claim 2, wherein the act of searching comprises:

computing values of a portion of the electrical properties of the model lines using a reference equation.

11. The method of claim 2, wherein the one-ended measurements are performed at a plurality of frequencies.

12. The method of claim 11, further comprising:

calculating a value of signal attenuation for the subscriber line from the one-ended measurements; and

increasing the calculated value in response to determining that the line has a bridged tap.

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13. A method of qualifying a subscriber line for a data service, comprising:

searching a reference set of model lines for a best match to a subscriber line by comparing sets of electrical properties;

determining that the subscriber line has a specific physical structure in response to the best matching model line having the specific physical structure; and

disqualifying the subscriber line for the data service, in part, in response to determining that the specific physical structure corresponds to a disqualified line.

14. The method of claim 13, wherein the electrical properties are obtained from one-ended measurements on the subscriber line.

15. The method of claim 14, wherein the act of searching for a best match comprises:

evaluating an error function for each model line to determine quality of correspondence between the electrical properties of the model line and of the subscriber line.

16. The method of claim 14, wherein the compared properties include a quantity indicative of the phase an impedance of the subscriber line.

17. The method of claim 14, further comprising:

making one-ended electrical measurements on the subscriber line at a plurality of frequencies to obtain the electrical properties.

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18. The method of claim 17, further comprising:

calculating a value of signal attenuation for the subscriber line from the one-ended measurements; and

increasing the value in response to determining that the line has a bridged tap.

19. The method of claim 18, wherein the act of disqualifying is responsive to the increased value being greater than a predetermined threshold value for the data service.

20. The method of claim 17, wherein the one-ended measurements determine one of a tip-to-ring admittance, a tip-to-ground admittance, and a ring-to-ground admittance.

21. The method of claim 17, wherein the making one-ended measurements includes driving the subscriber line through a test access of a switch or DSLAM device.

22. A method of providing a data service, comprising:

searching a reference set of model lines for a best match to a subscriber's line by comparing measured electrical properties to properties of the model lines;

determining whether the subscriber's line is qualified for the data service based in part on whether the best matching model line has a one of a bridged tap and a mixture of gauges; and

performing a business action in response to determining that the subscriber's line is qualified.

23. The method of claim 22, wherein the business

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action includes offering one of the data service and a service quality-level agreement to the subscriber.

24. The method of claim 22, wherein the act of offering comprises:

performing one of a repair and a replacement of the subscriber line in response to determining that subscriber line is disqualified.

25. The method of claim 22, further comprising:

repeating the acts of searching, determining, and performing for a plurality of subscriber lines connected to one telephony switch or one DSLAM device.

26. The method of claim 22, wherein the act of searching for a best match comprises:

evaluating an error function for each model line to determine quality of a correspondence between the electrical properties of the model line and the subscriber line.

27. The method of claim 22, wherein the compared properties include a quantity indicative of a phase of an impedance of the subscriber line.

28. The method of claim 22, further comprising:

performing one-ended electrical measurements at a plurality of frequencies to obtain the electrical properties.

29. The method of claim 22, wherein the act of determining further comprises:

calculating a value of a signal attenuation for the

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subscriber line from the one-ended measurements;

increasing the value in response to determining that the line has a bridged tap or a mixture of gauges; and

wherein the act of qualifying is responsive to the increased value being less than a predetermined threshold value for the data service.

30. A data storage device storing an executable program of instructions for determining a structure of a subscriber line, the instructions to cause a computer to:

search a reference set for a match between the subscriber line and a model line of a reference set, the match being based on electrical properties of the lines; and

identify that the subscriber line has a specific physical structure in response to finding a match with one of the model lines that has the specific physical structure.

31. The device of claim 30, wherein the electrical properties are determined from one-ended measurements.

32. The device of claim 30, wherein the instructions to search cause the computer to:

evaluate an error function for each model line to determine quality of the match between values of the electrical properties of the model and subscriber lines.

33. The device of claim 30, wherein the electrical properties include a quantity representative of a phase of an impedance of the subscriber line.

34. The device of claim 31, wherein the

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instructions to identify cause the computer to indicate that the subscriber line has one or more bridged taps in response to the matching model line having one or more bridged taps.

35. The device of claim 31, wherein the instructions to identify cause the computer to indicate that the subscriber line has a mixture of gauges in response to the matching model having a mixture of gauges.

36. The device of claim 31, wherein the electrical properties in a property at a plurality of frequencies.

37. The device of claim 31, the instructions further causing the computer to:

calculate a value of signal attenuation for the subscriber line from the one-ended measurements; and

increase the calculated value in response to determining that the line has a bridged tap.

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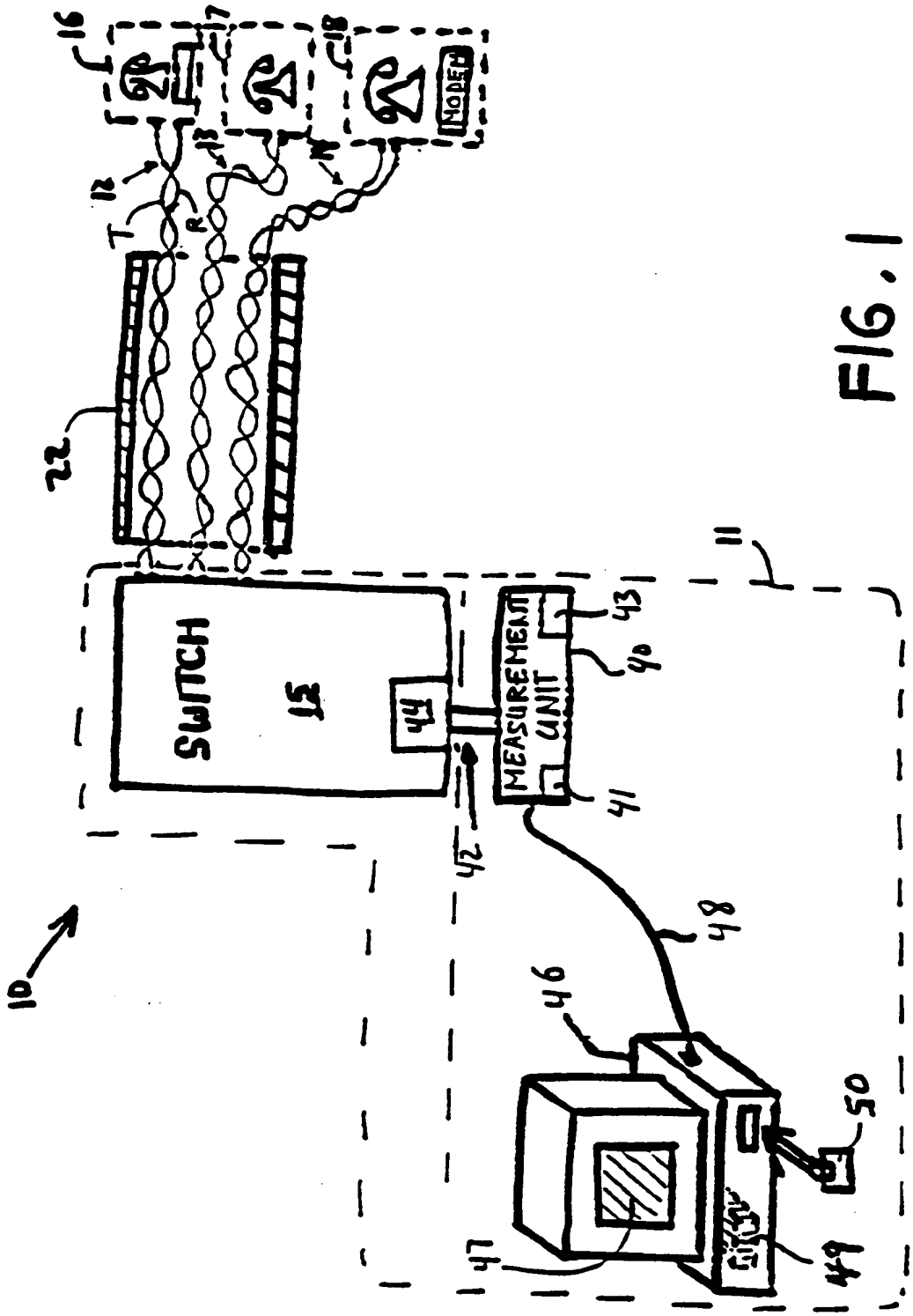

FIG. 1

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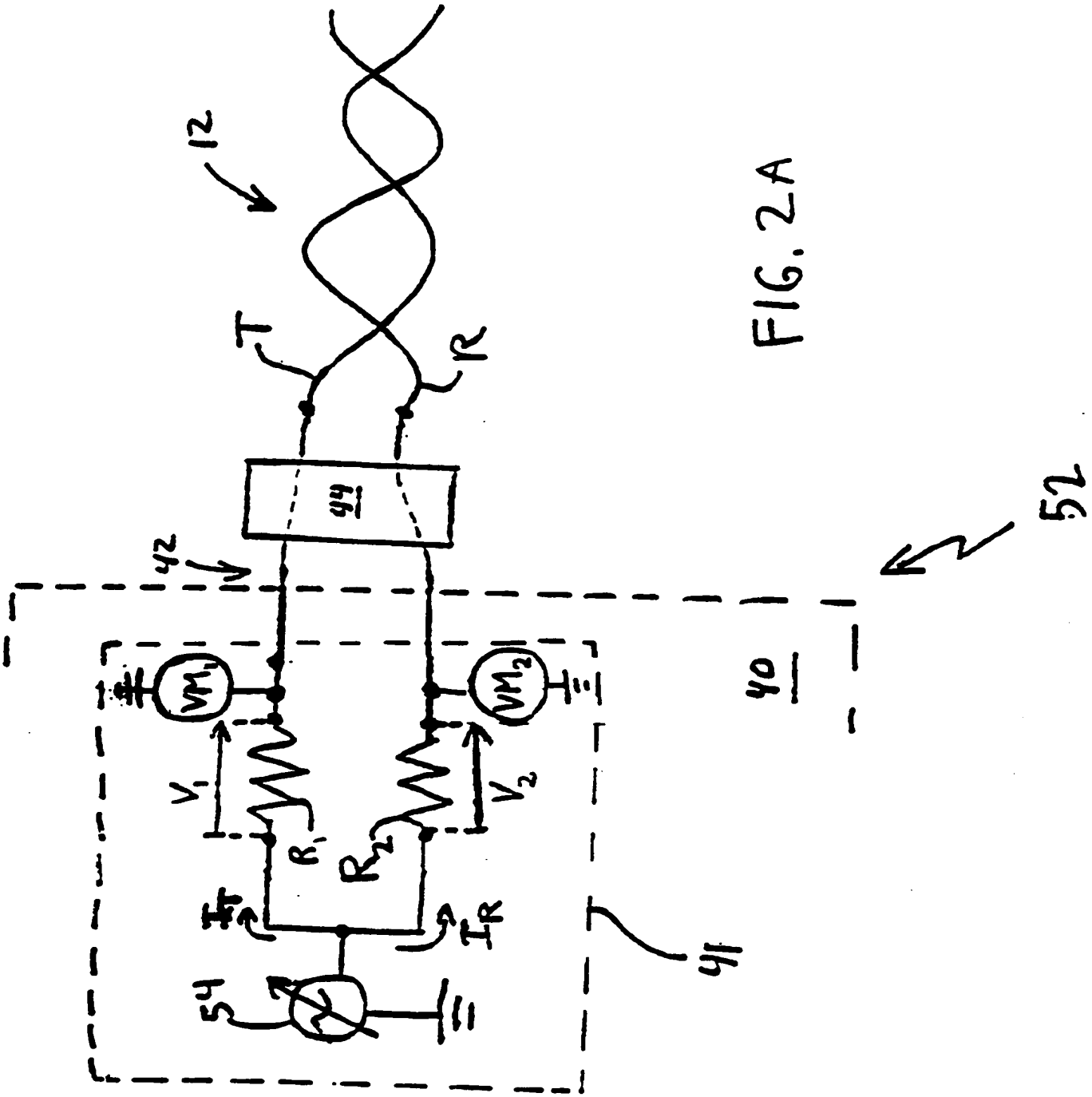

FIG. 2A

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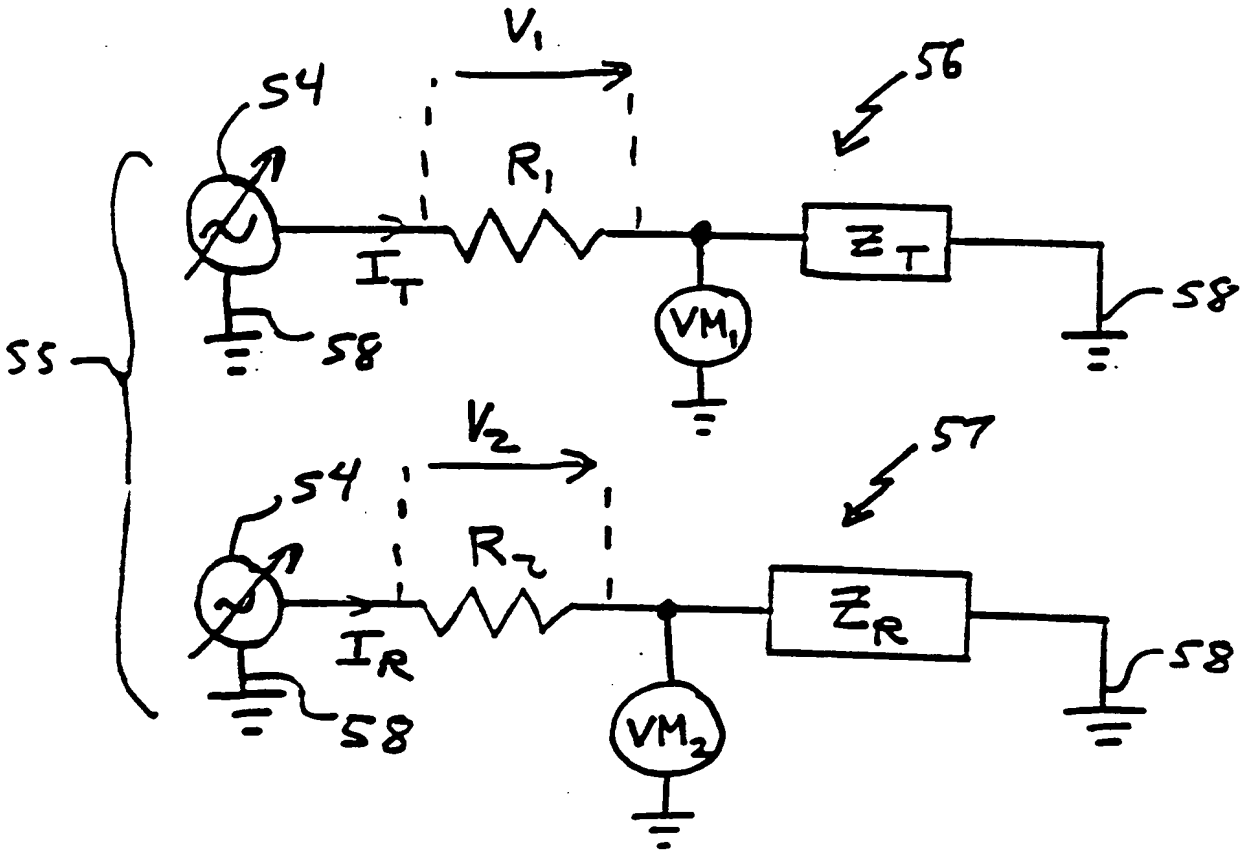

FIG. 2B

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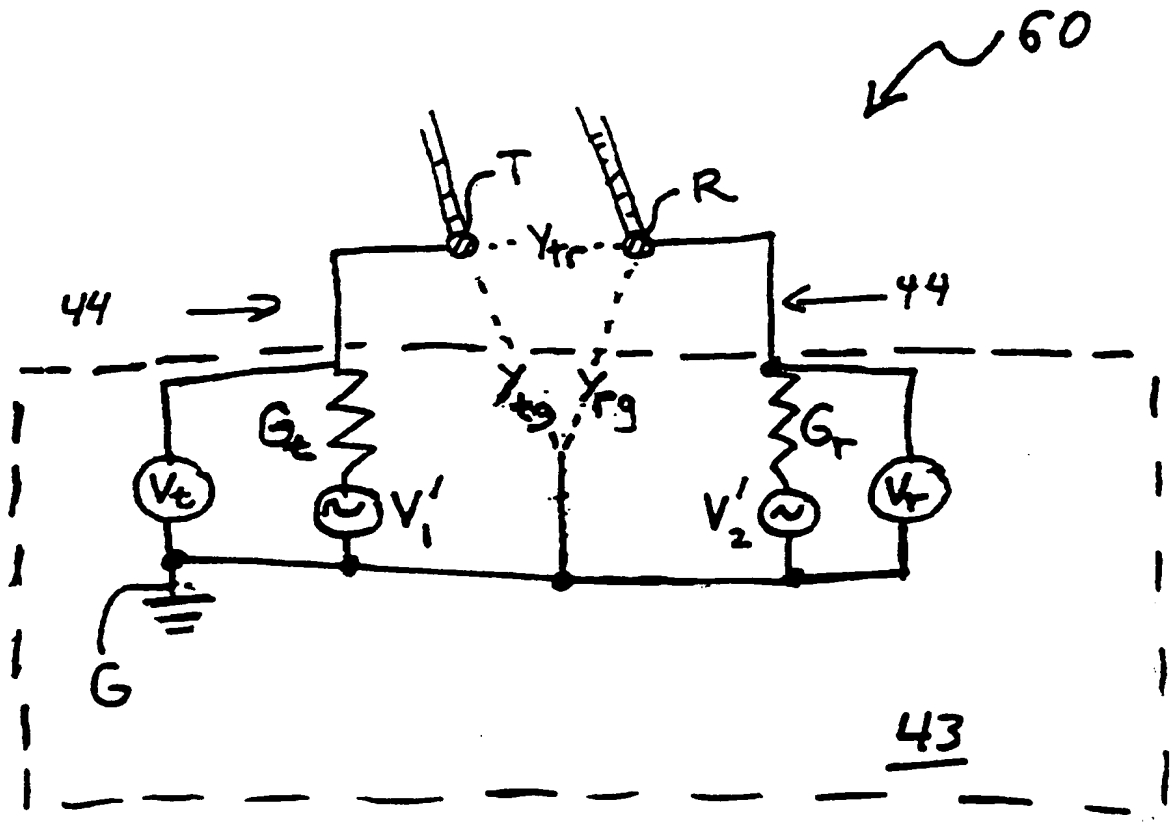

FIG. 2C

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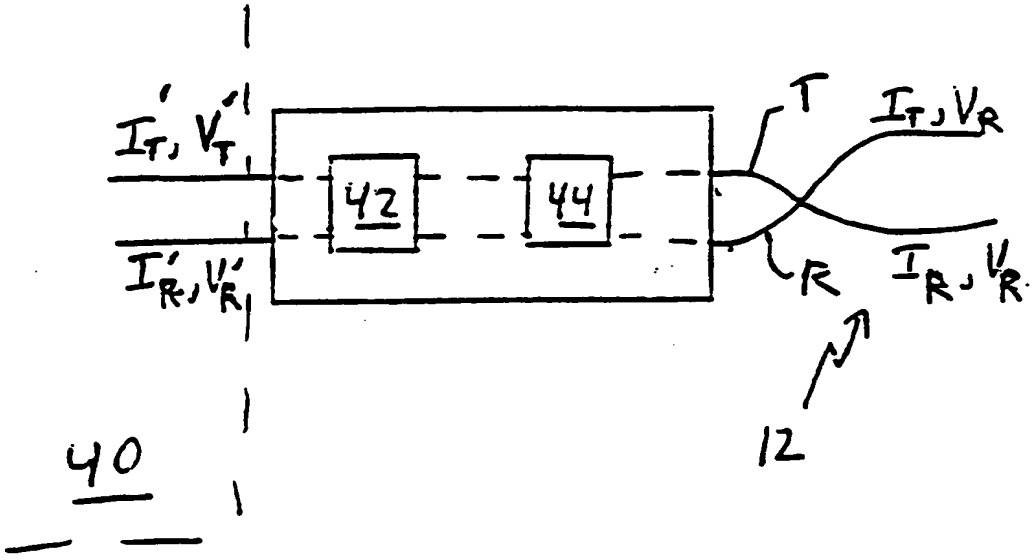

FIG. 3

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FIG. 4

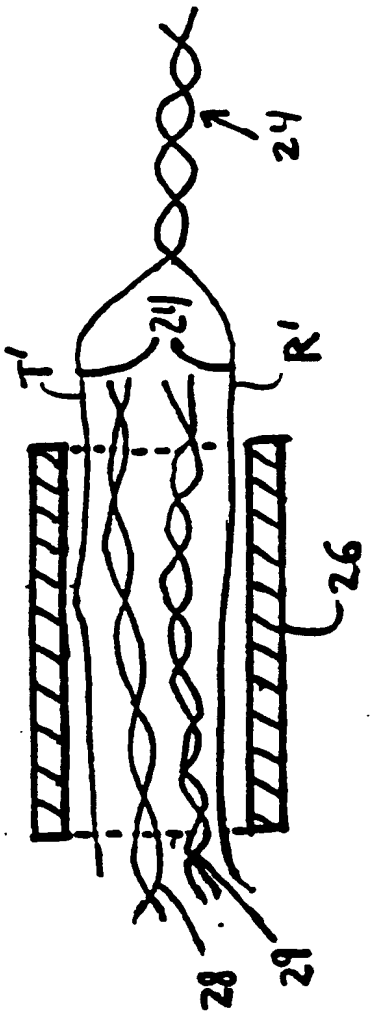
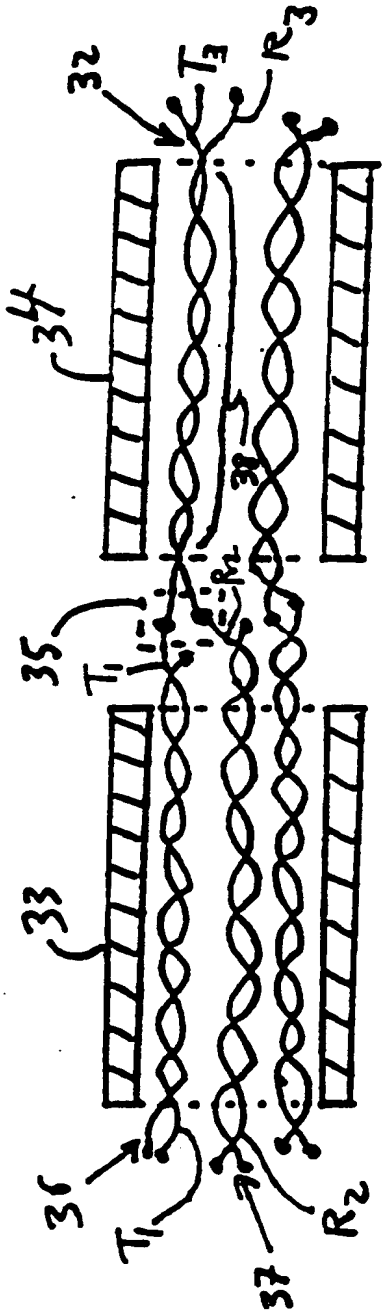


FIG. 5



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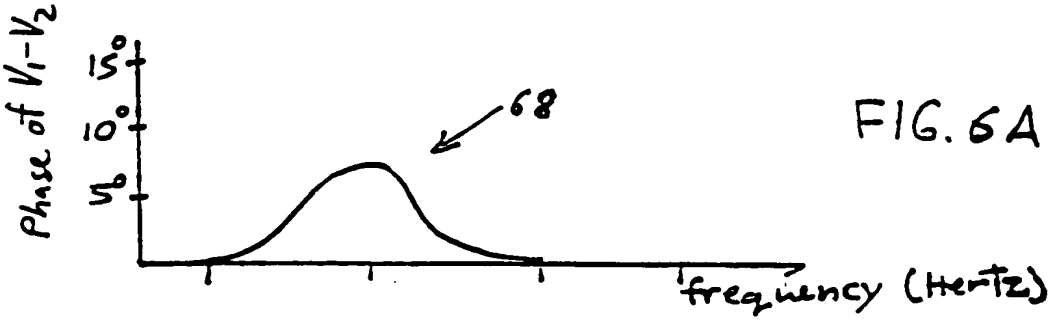

FIG. 6A

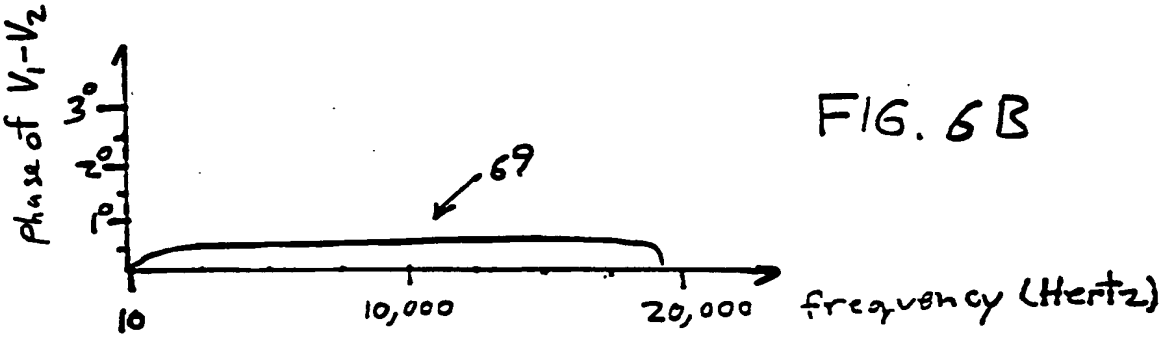

FIG. 6B

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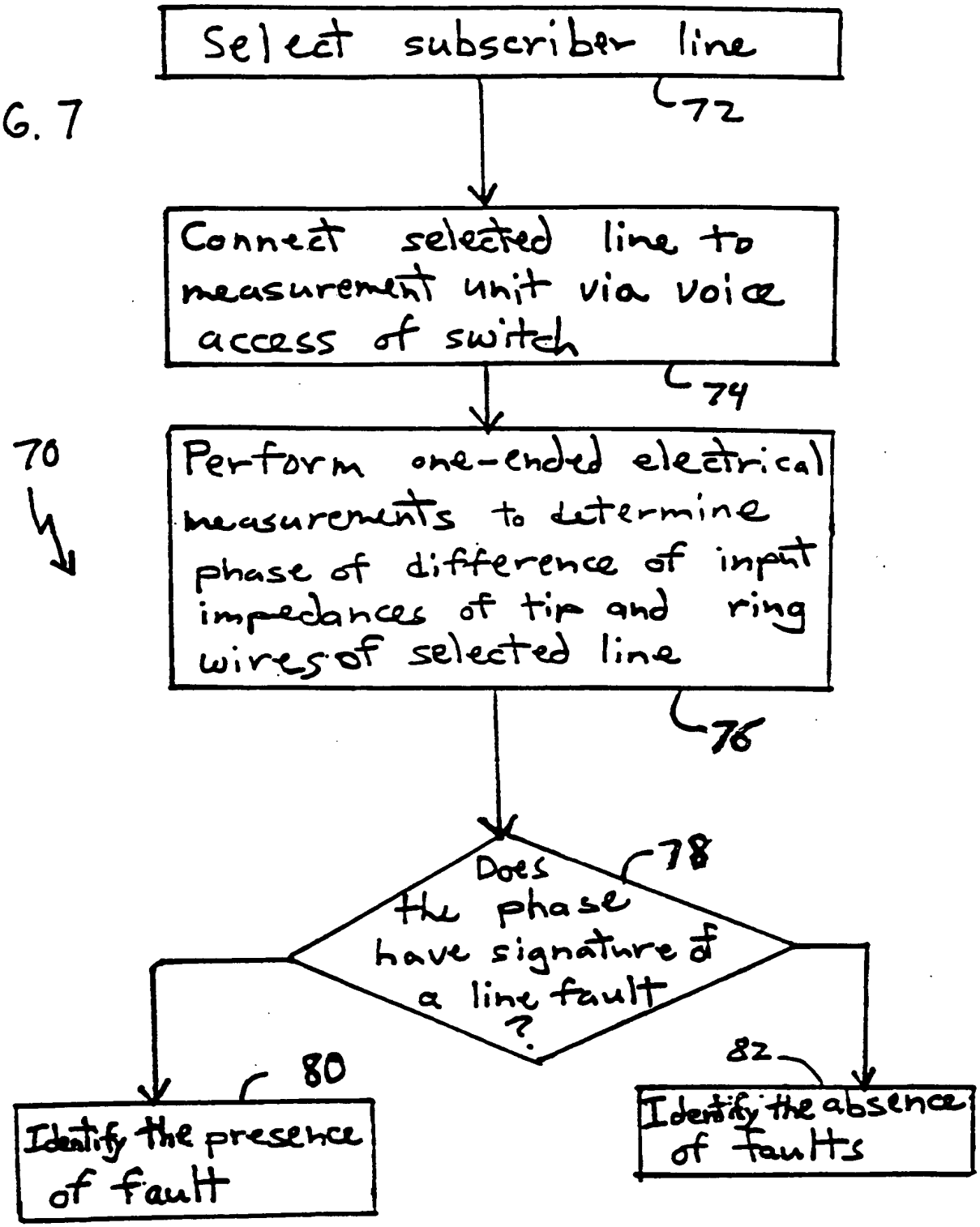
FIG. 7



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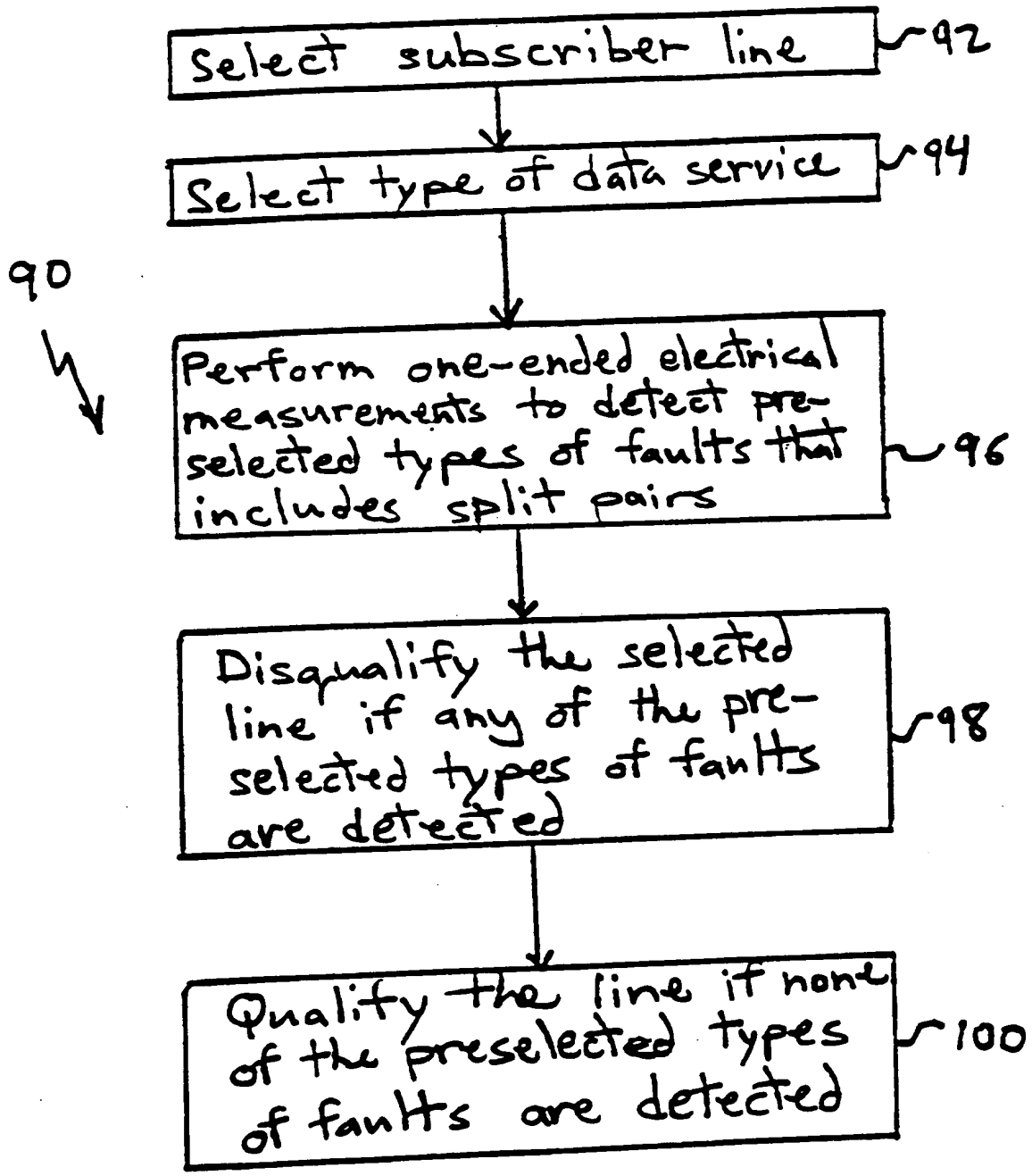

FIG. 8

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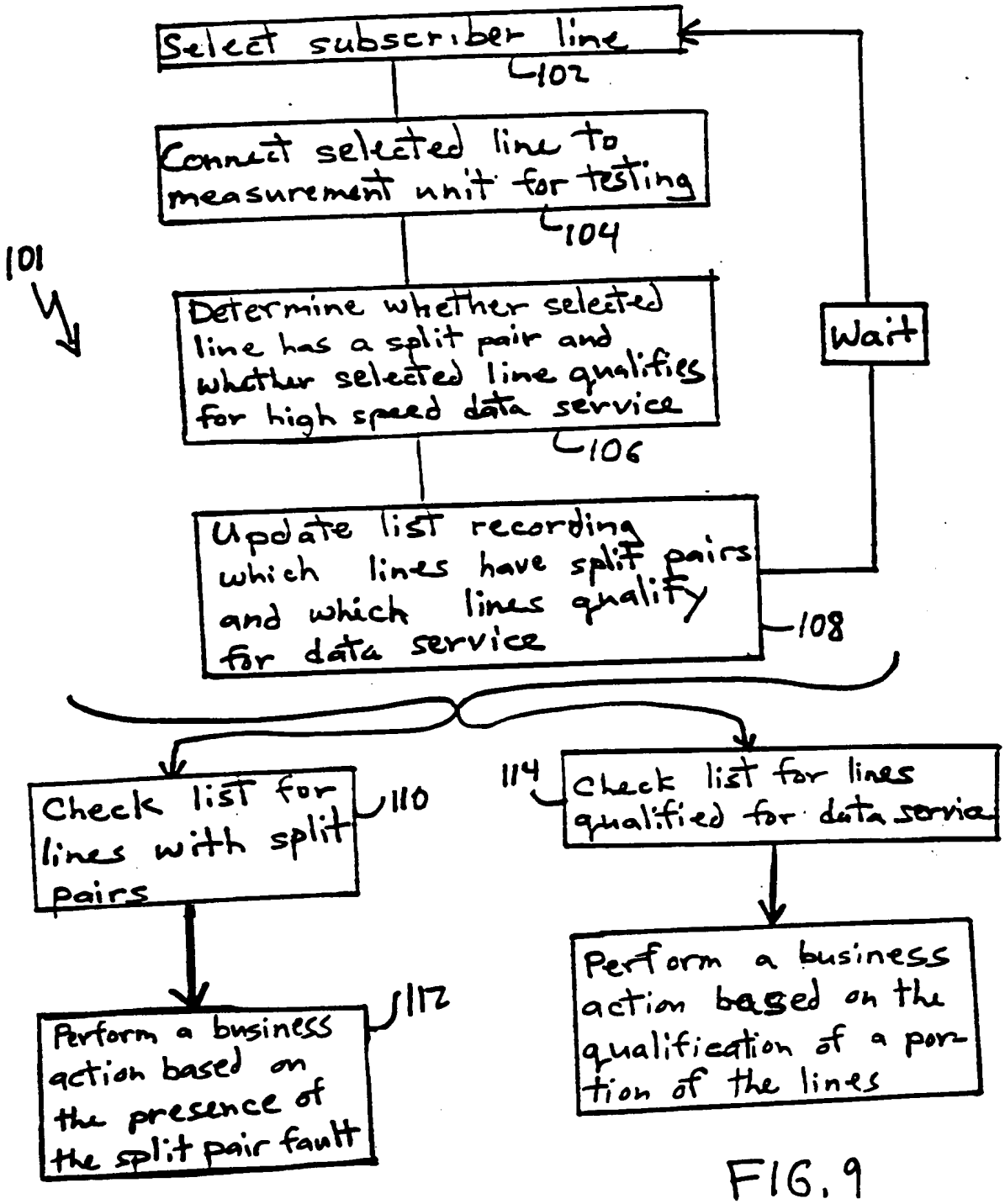
Select subscriber line
102
Connect selected line to measurement unit for testing
104
101
Determine whether selected line has a split pair and whether selected line qualifies for high speed data service
106
Wait
Update list recording which lines have split pairs and which lines qualify for data service
108
Check list for lines with split pairs
110
Perform a business action based on the presence of the split pair fault
112
114
Check list for lines qualified for data servia
Perform a business action based on the qualification of a portion of the lines

FIG. 9

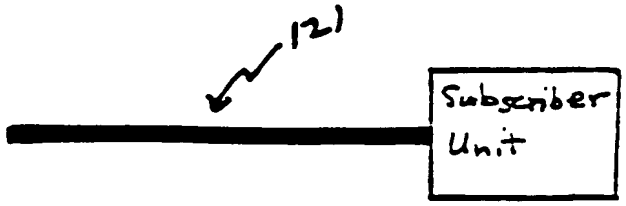

FIG. 10A

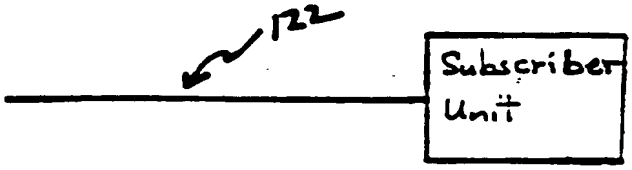

FIG. 10B

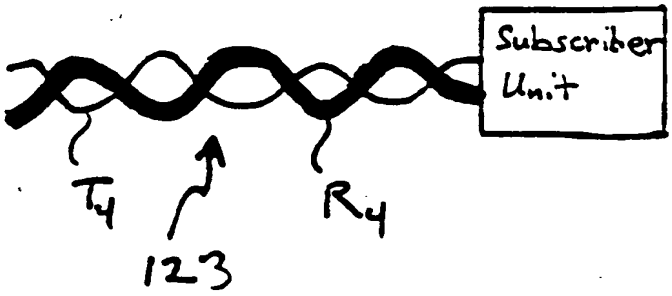

FIG. 10C

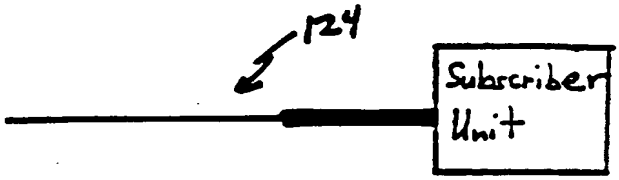

FIG. 10D

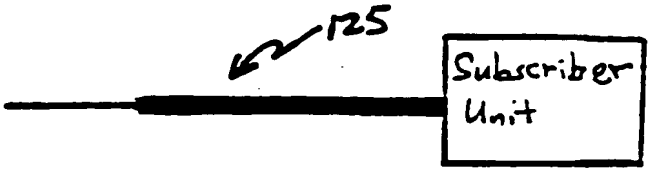

FIG. 10E

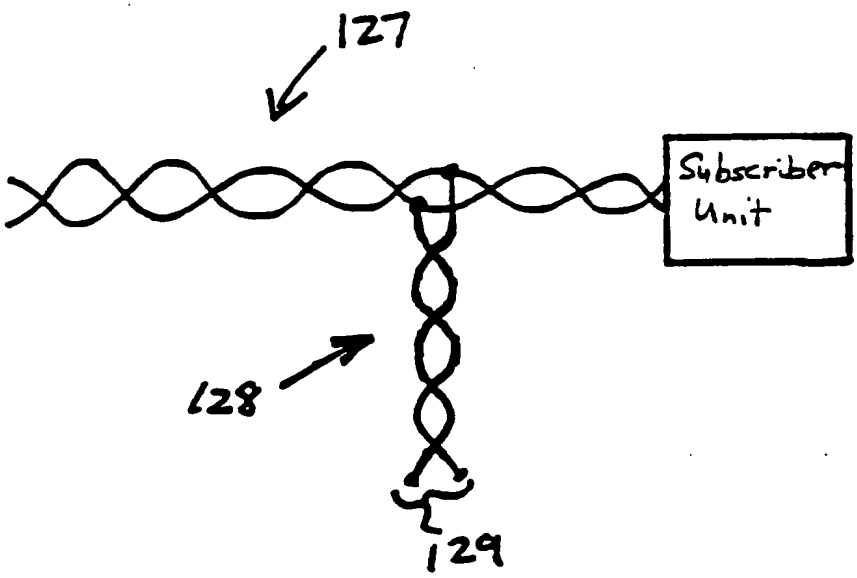

FIG. 11

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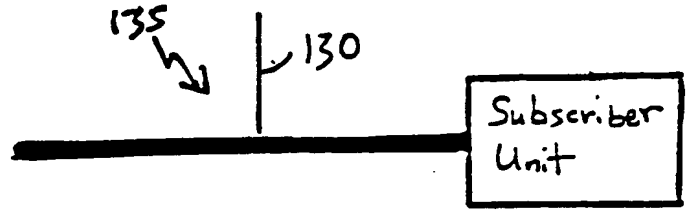


FIG. 12 A

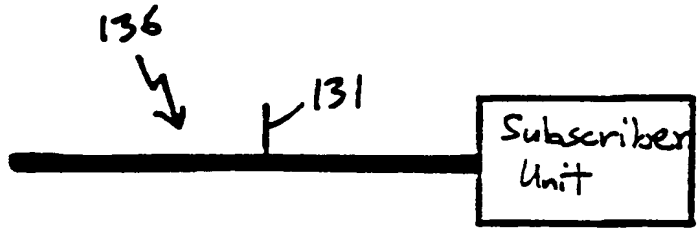


FIG. 12 B

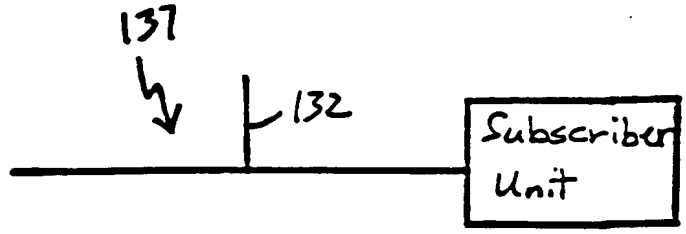


FIG. 12 C

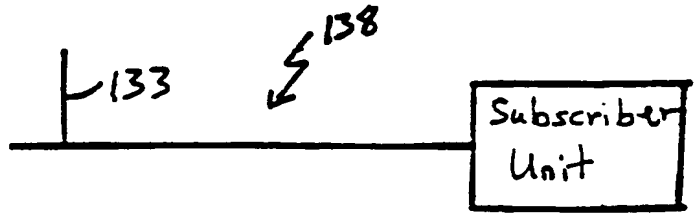


FIG. 12 D

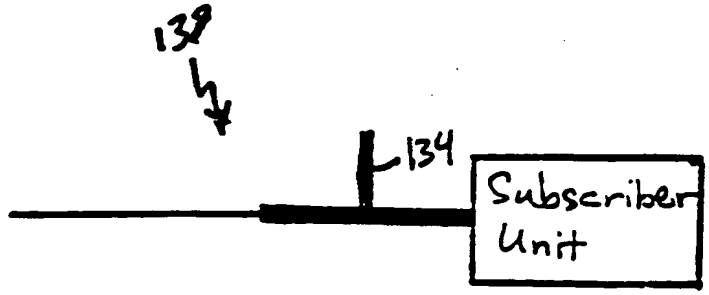


FIG. 12 E

BNSDOCID: <WO 0064130A2 I >

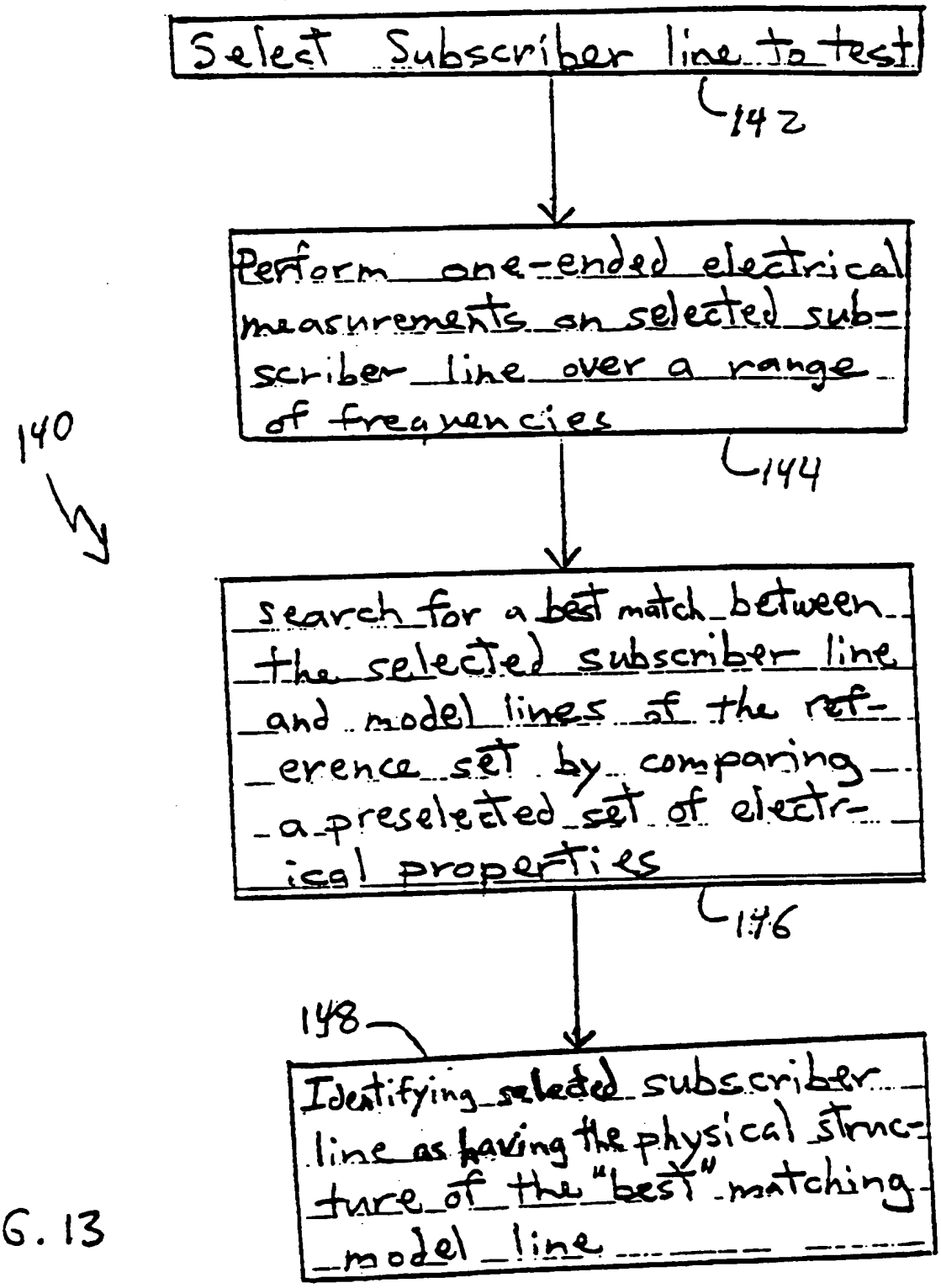


FIG. 13

BNSDOCID: <WO 0064130A2 I >

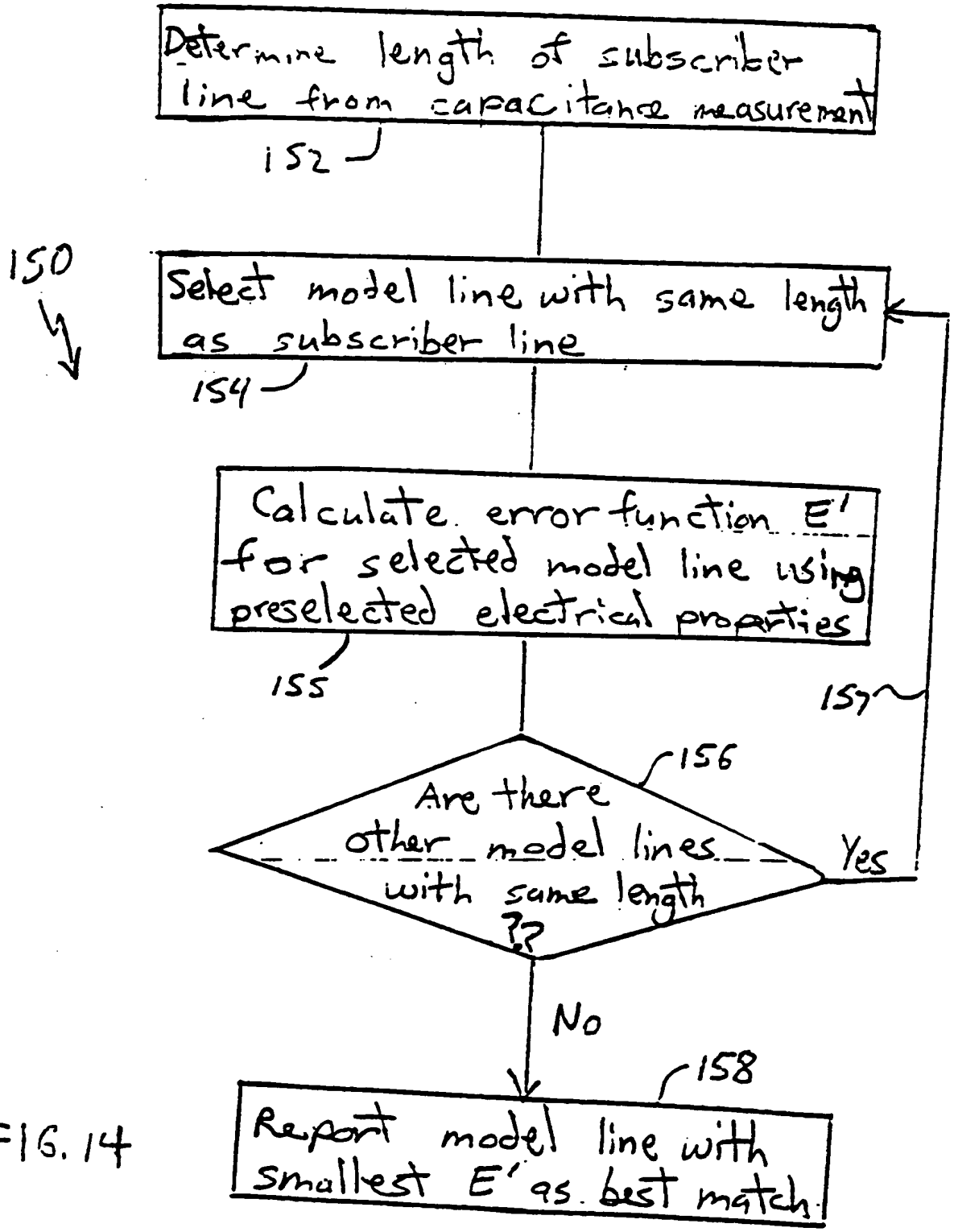

Determine length of subscriber line from capacitance measurement
152
150
Select model line with same length as subscriber line
154
Calculate error function E' for selected model line using preselected electrical properties
155
157
156
Are there other model lines with same length ??
Yes
No
158
Report model line with smallest E' as best match

FIG. 14

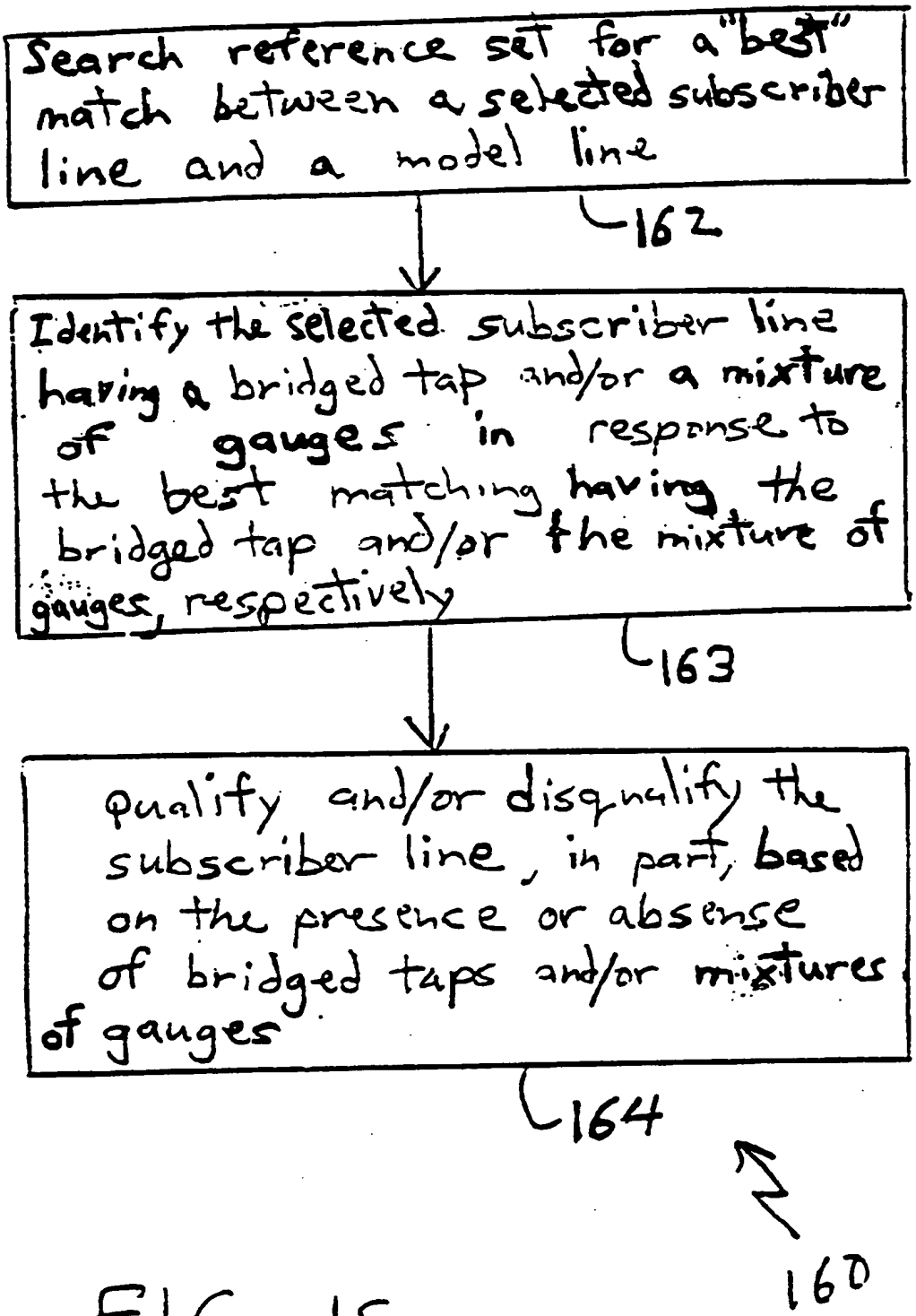


FIG. 15

BNSDOCID: <WO 0064130A2 I >

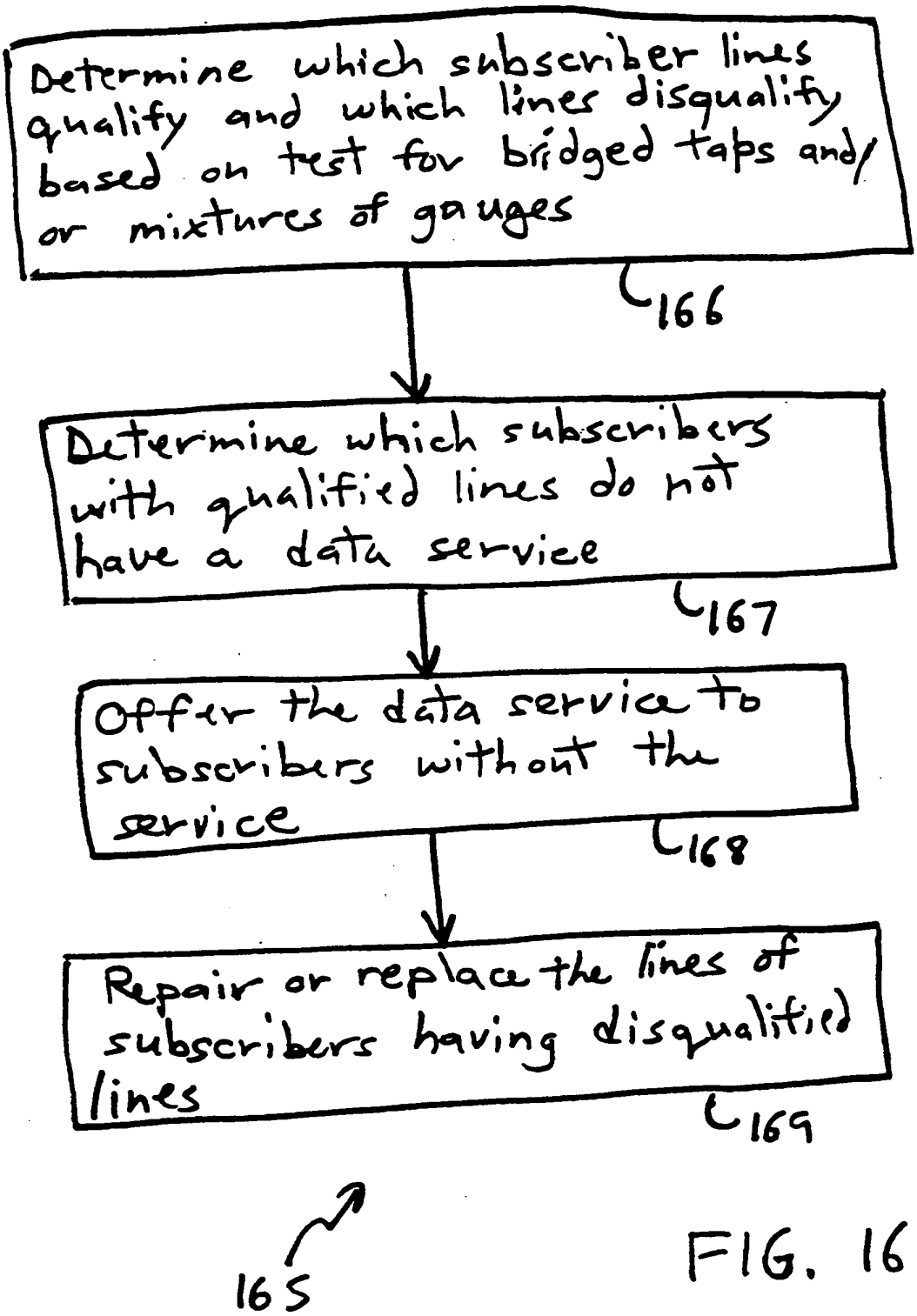


FIG. 16

BNSDOCID: <WO 0064130A2 I >

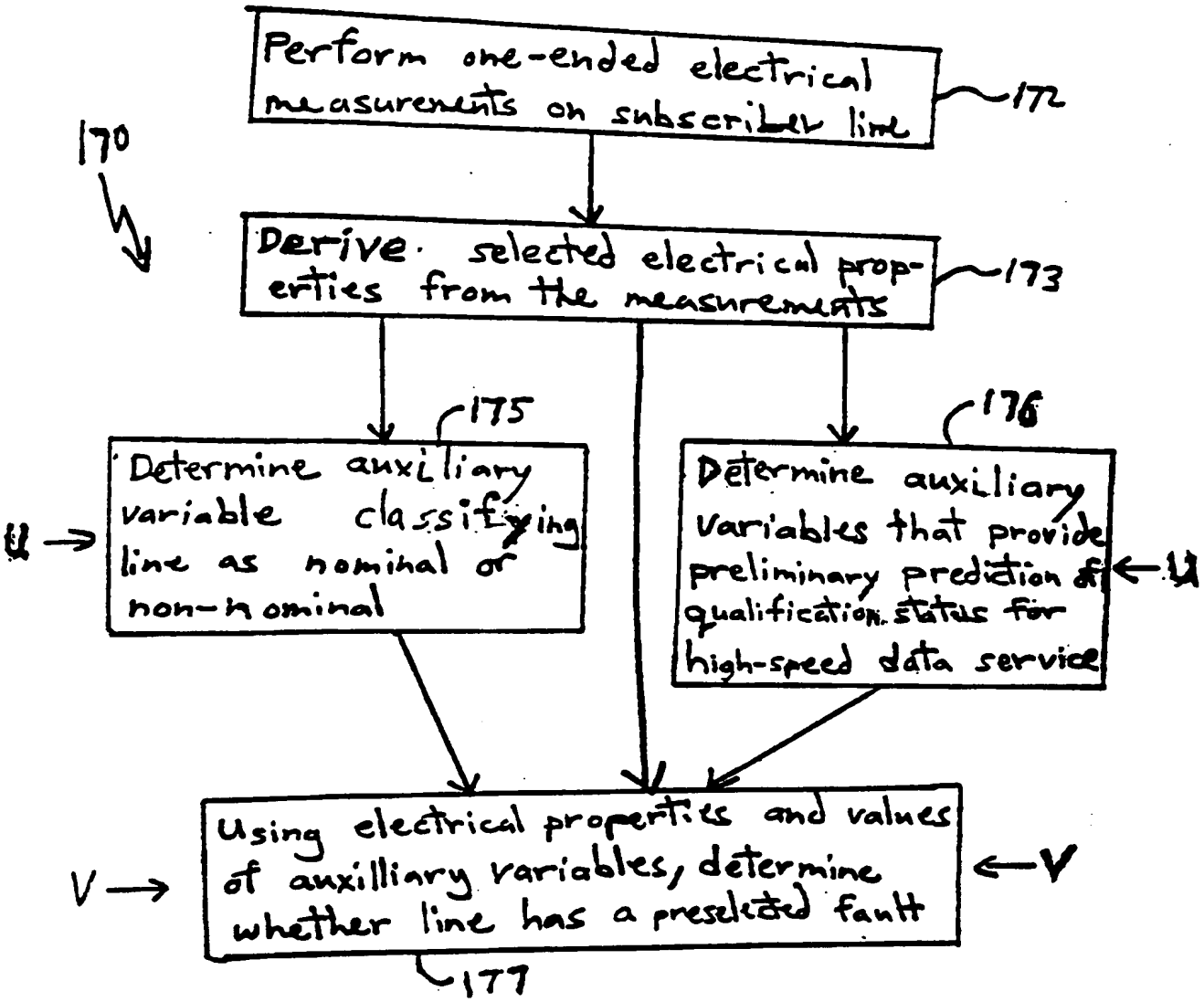
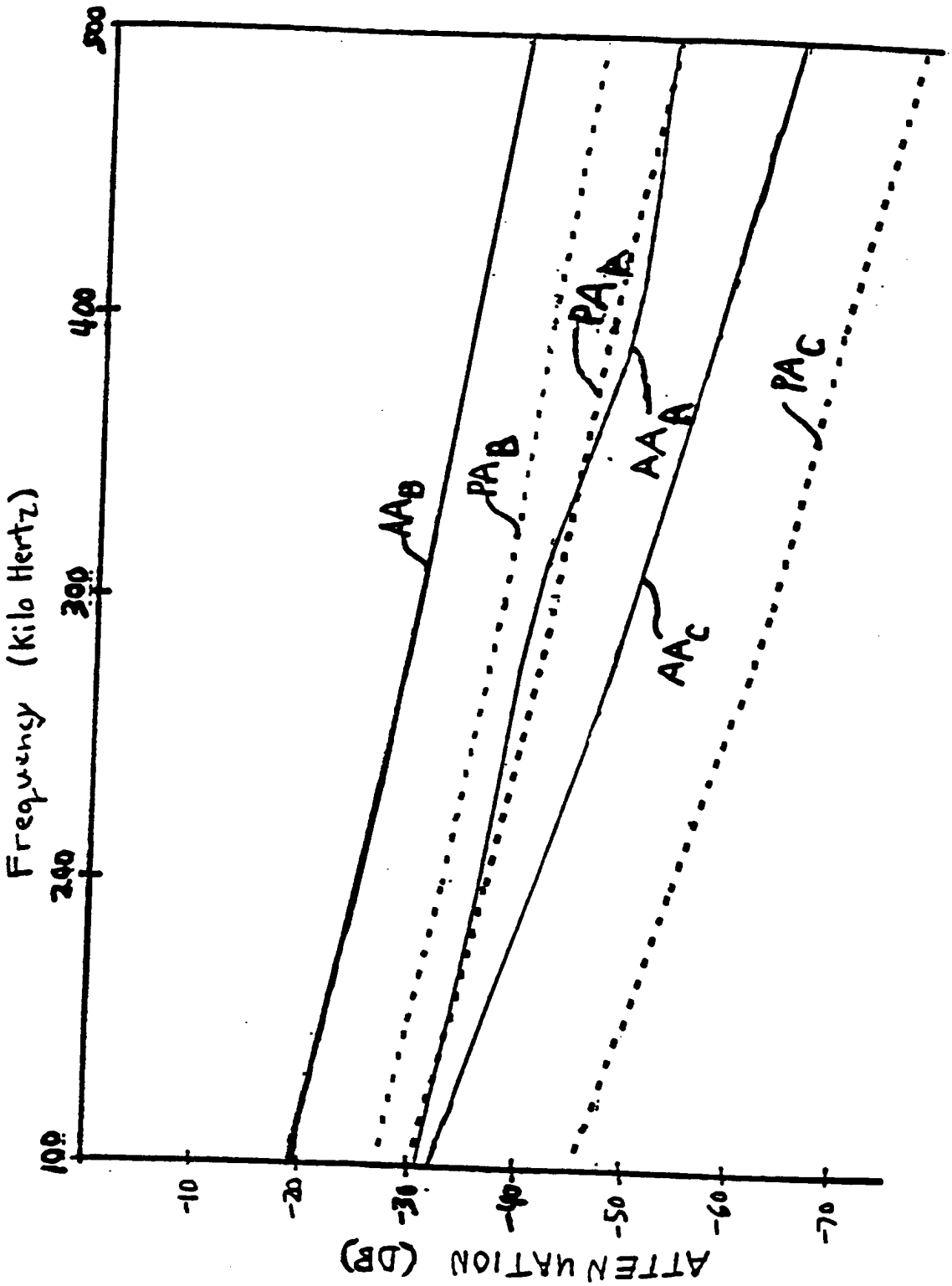


FIG. 17

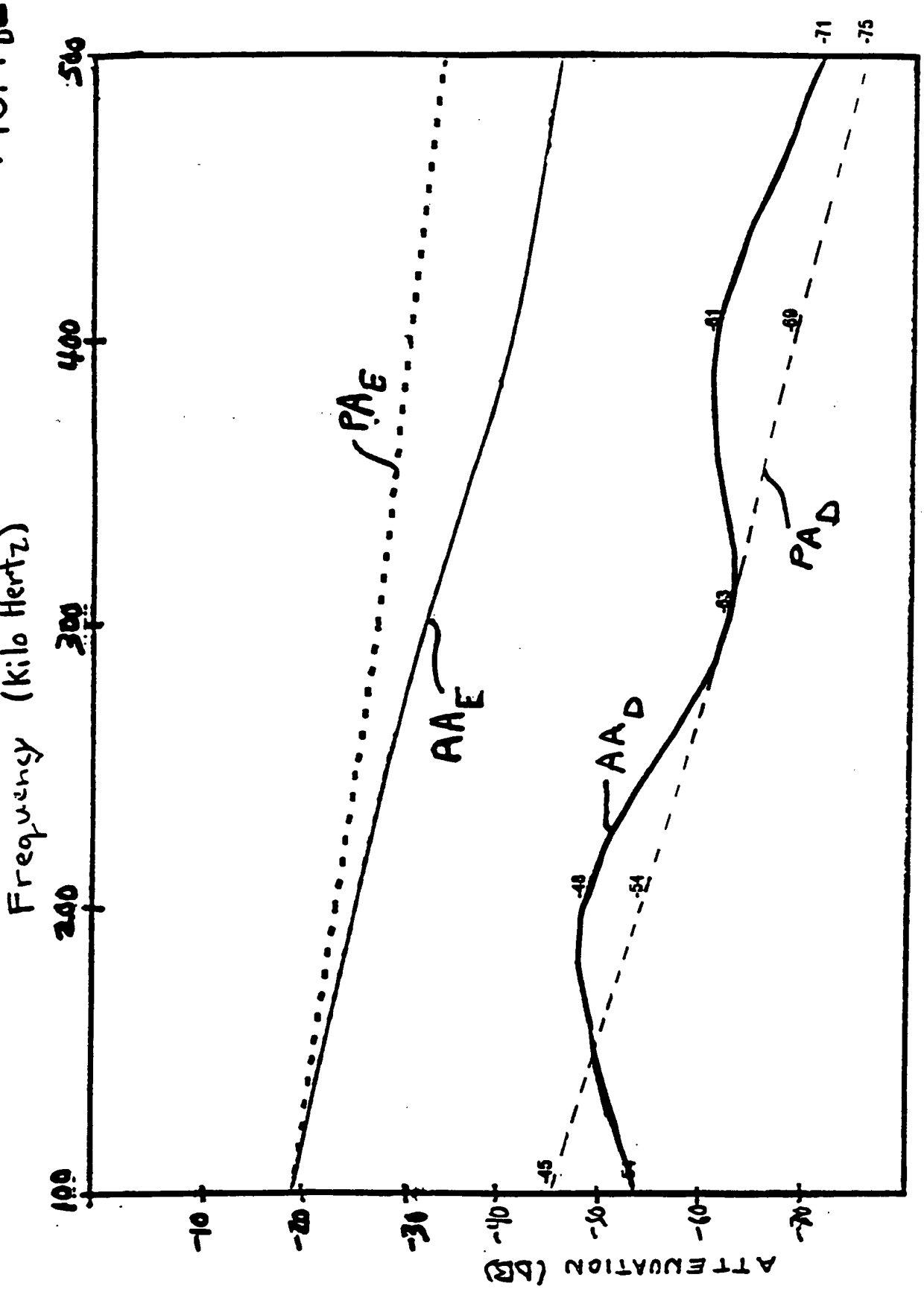
BNSDOCID: <WO 0064130A2 I >

FIG. 18A



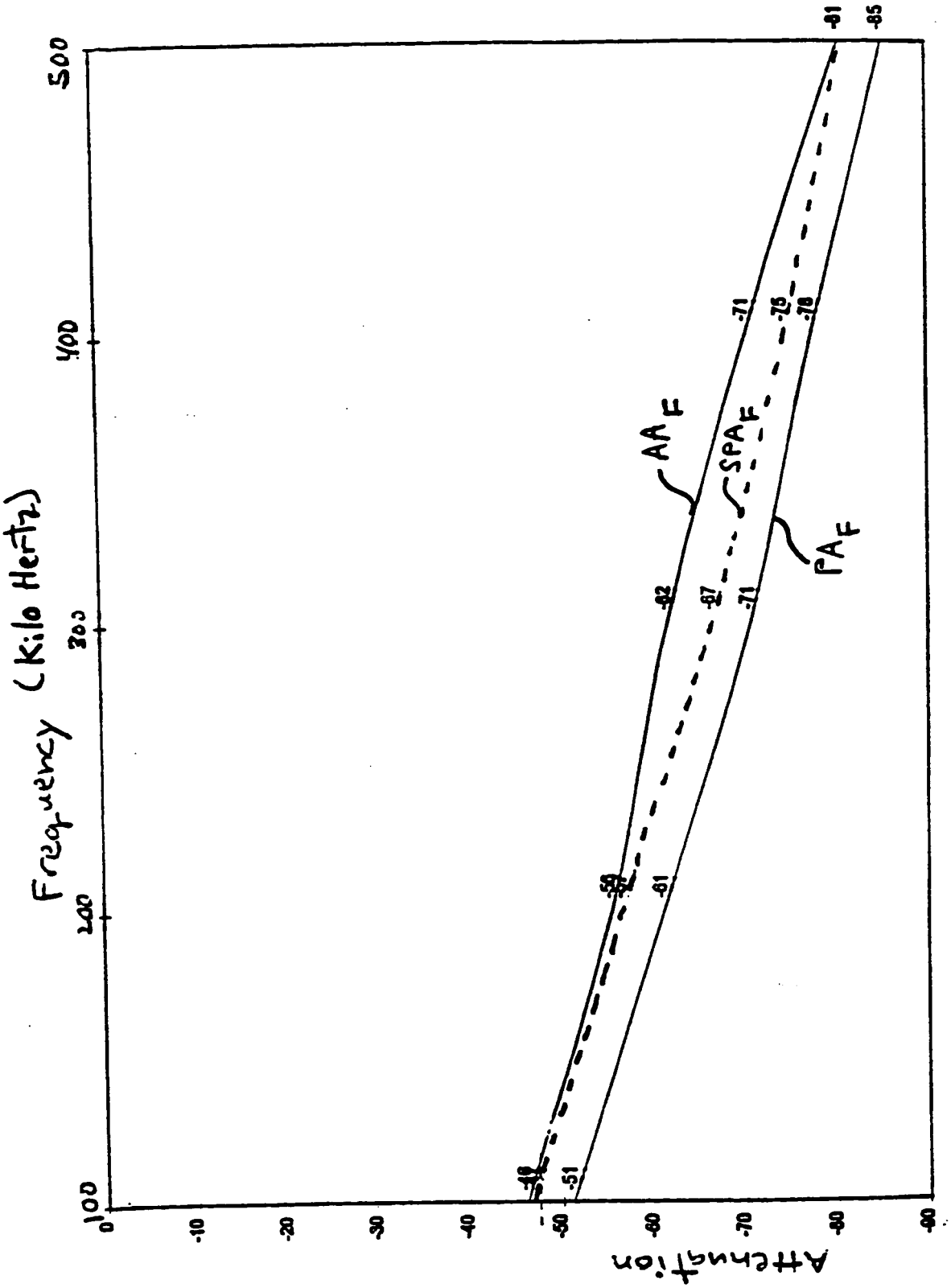
BNSDOCID: <WO 0064130A2 I >

FIG. 19B



BNSDOCID: <WO 0064130A2 I >

FIG. 18C



BNSDOCID: <WO 0064130A2 I >

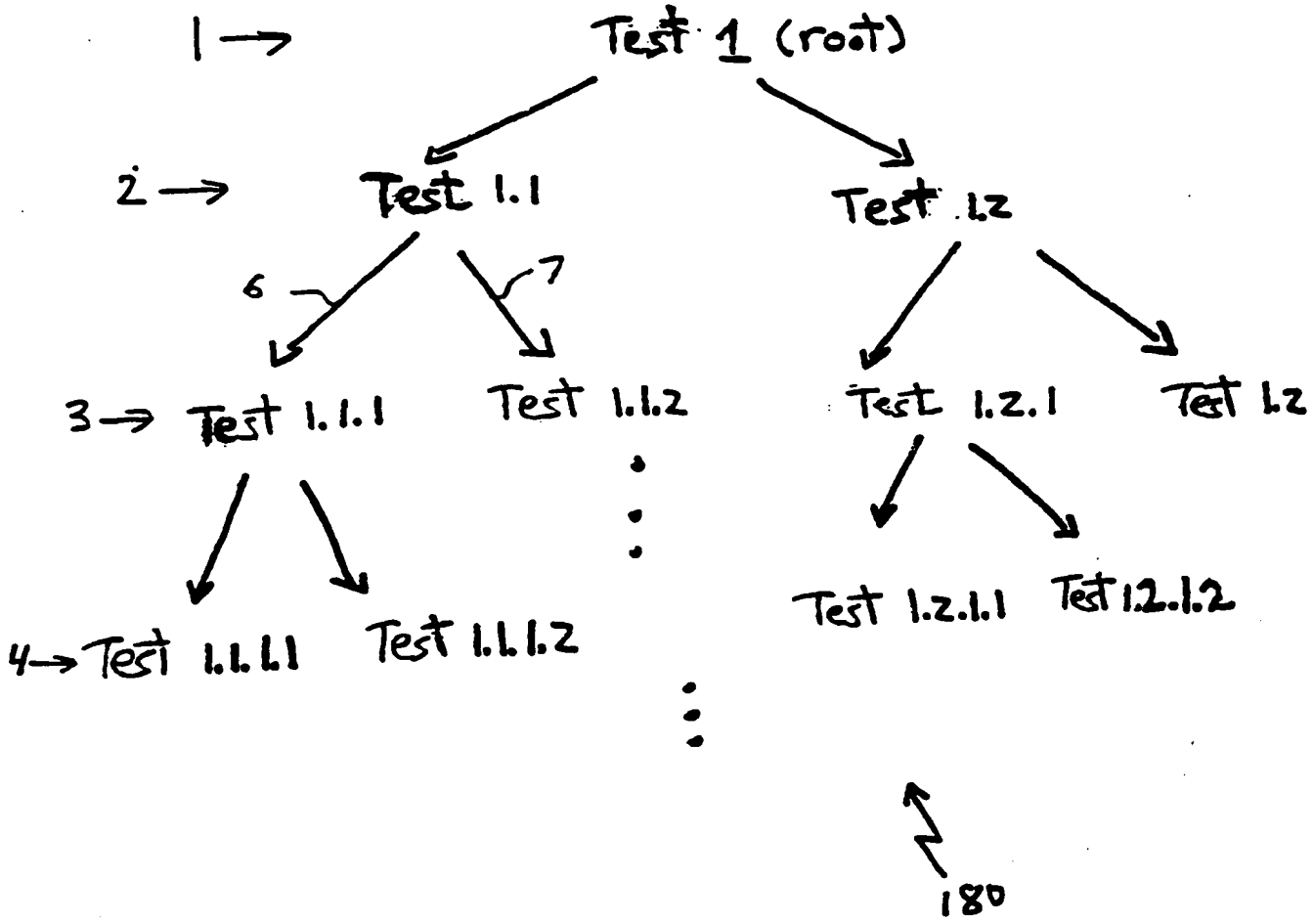
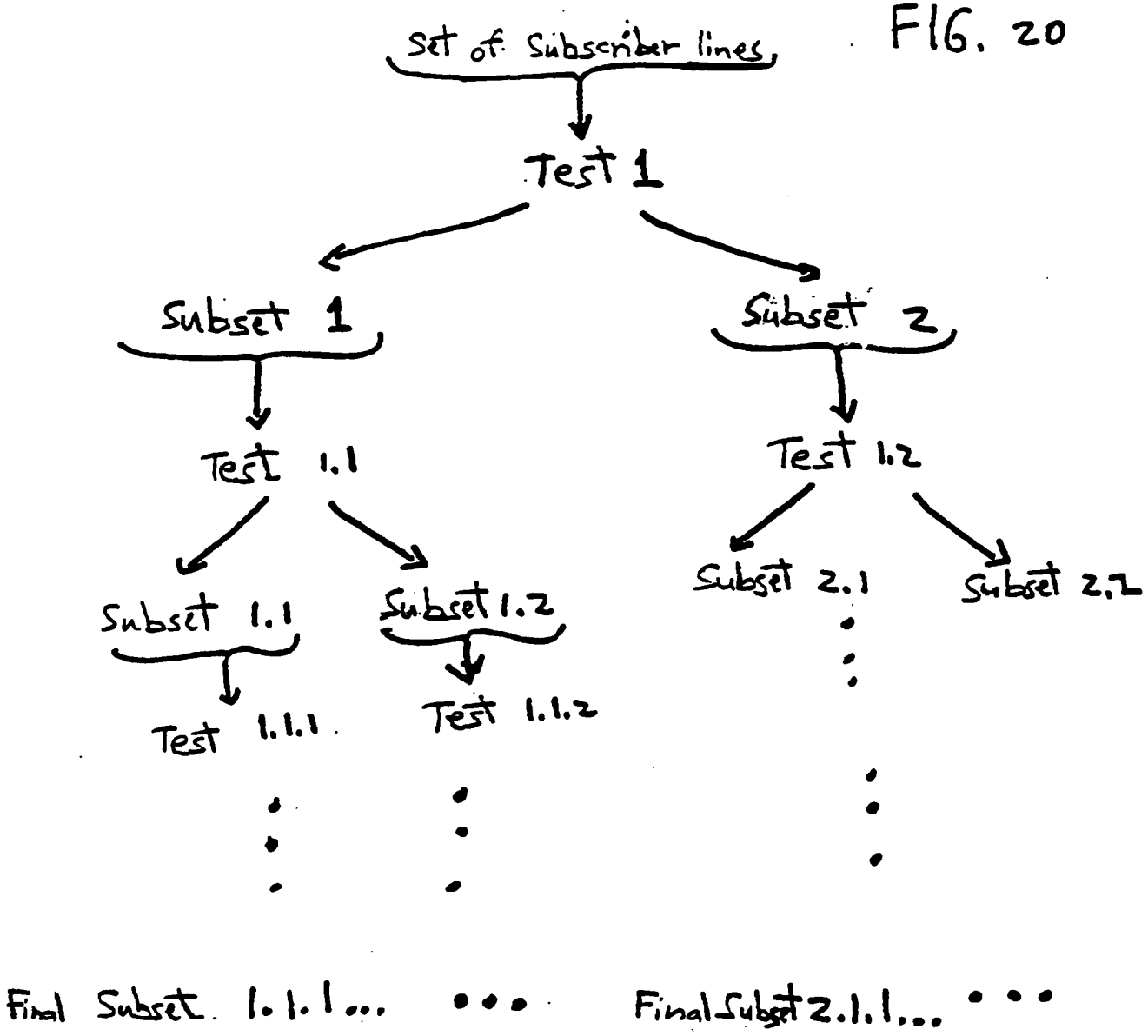


FIG. 19

BNSDOCID: <WO 0064130A2 I >

FIG. 20


Set of Subscriber lines
Test 1
Subset 1
Subset 2
Test 1.1
Test 1.2
Subset 1.1
Subset 1.2
Subset 2.1
Subset 2.2
Test 1.1.1
Test 1.1.2
Final Subset 1.1.1...
Final Subset 2.1.1...

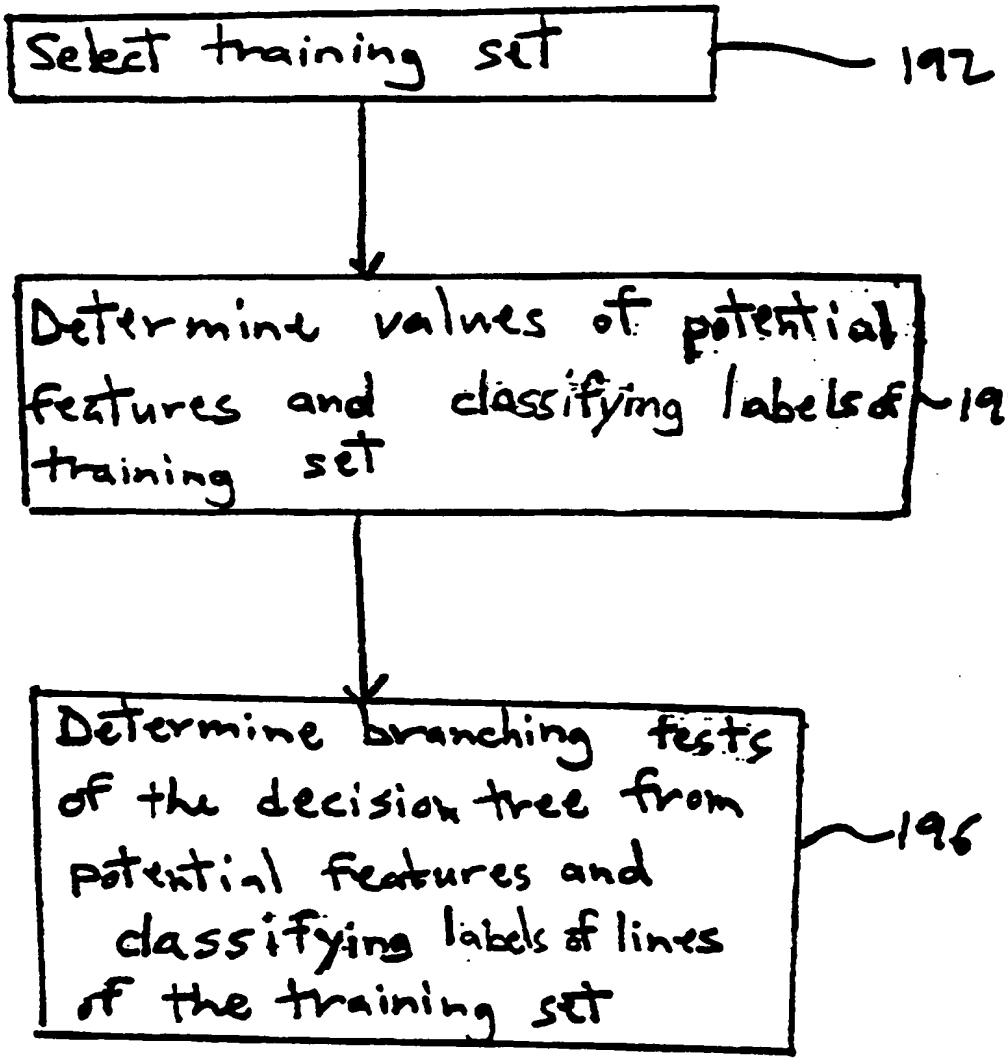


FIG. 21

BNSDOCID: <WO 0064130A2 I >

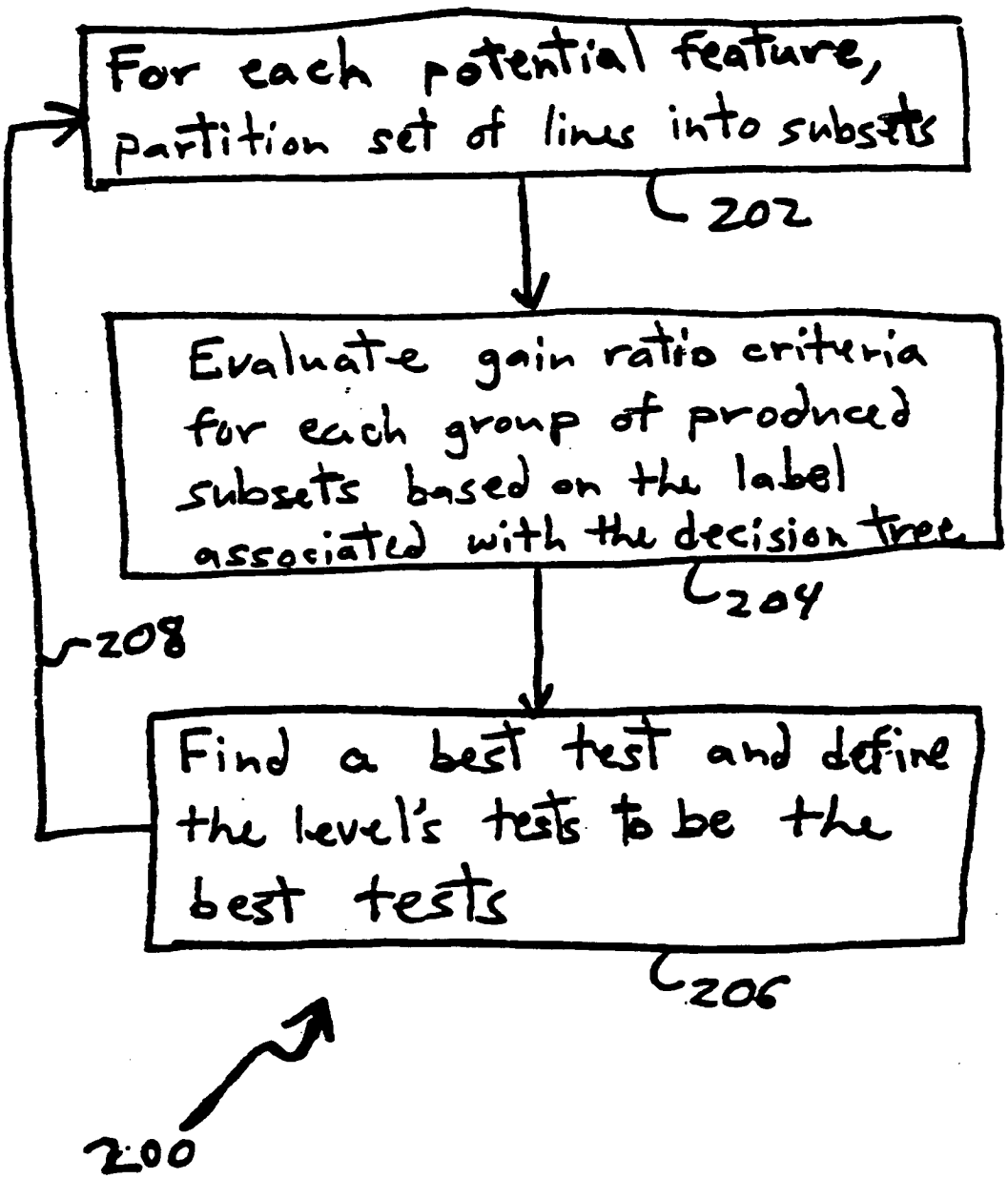


FIG. 22

BNSDOCID: <WO 0064130A2 I >

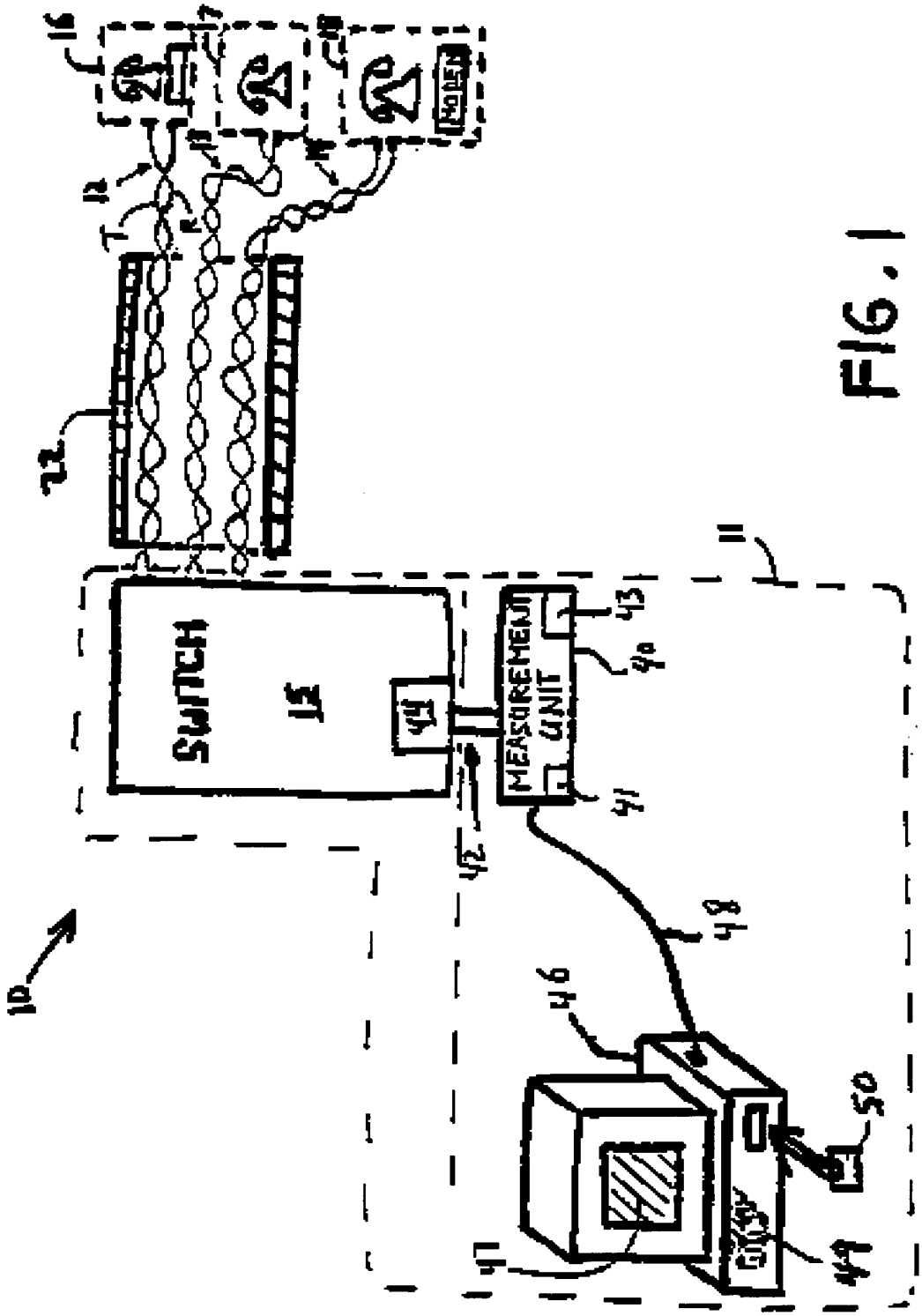


FIG. 1

BNSDOCID: <WO 0064130A2TI >

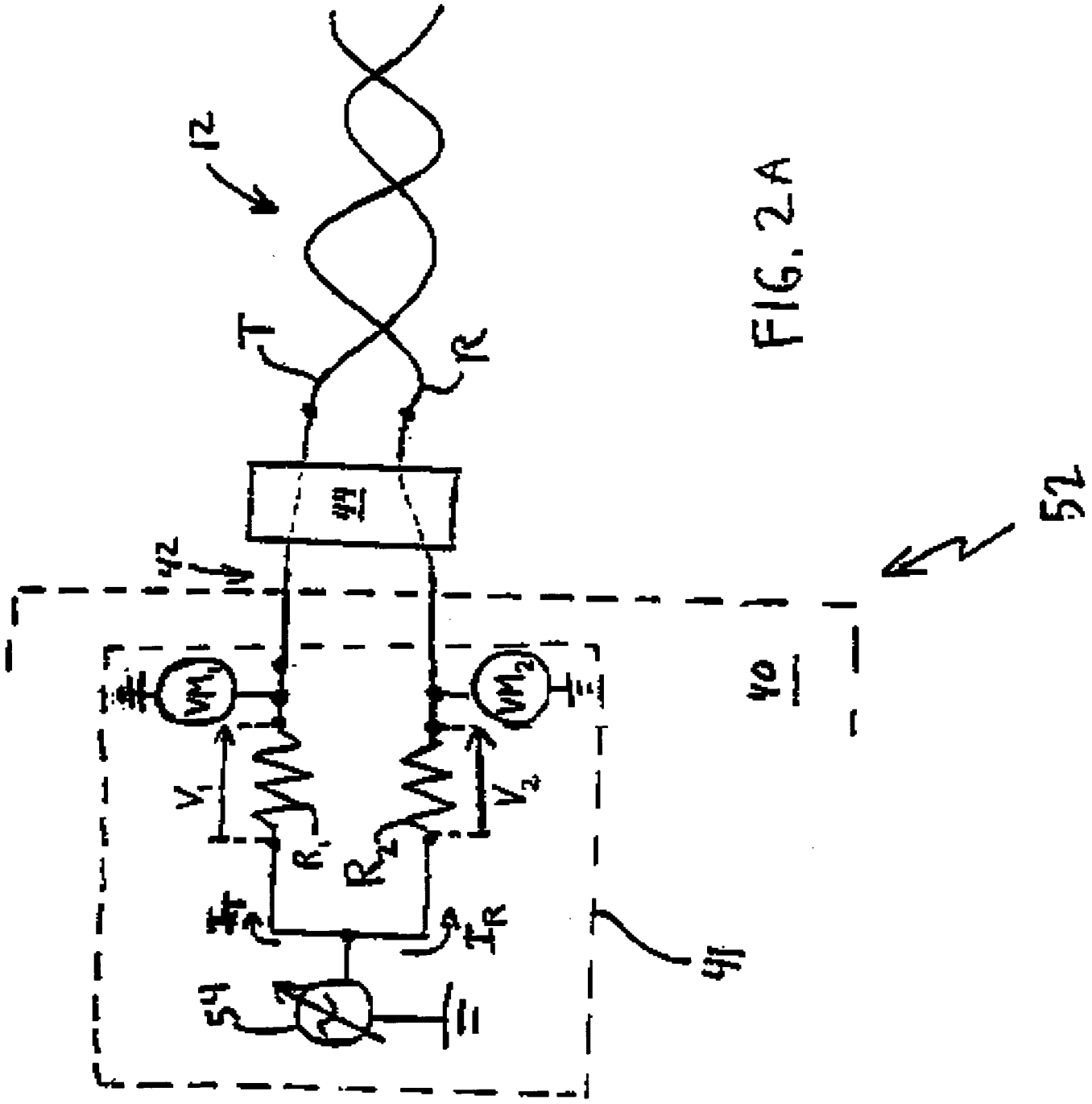


FIG. 2A

BNSDOCID: <WO 0064130A2TI >

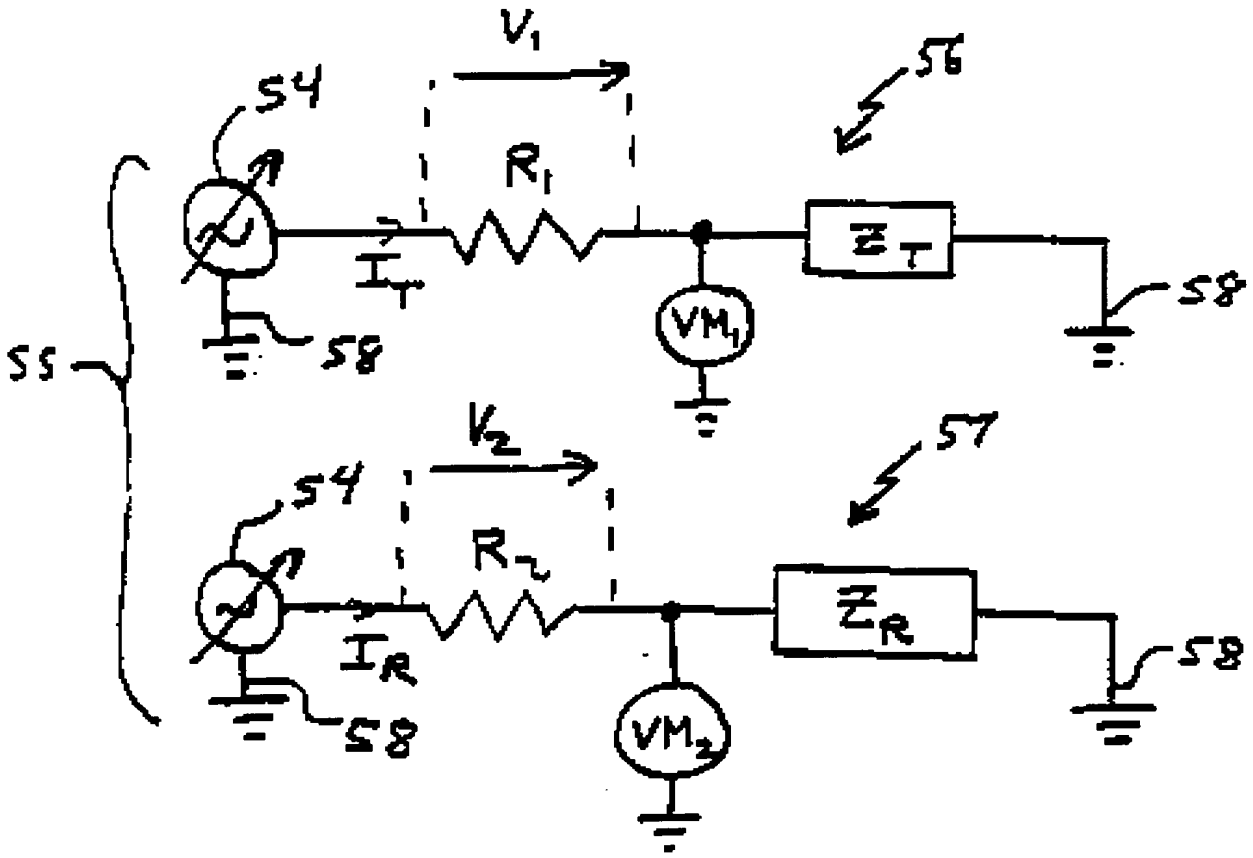


FIG. 2B

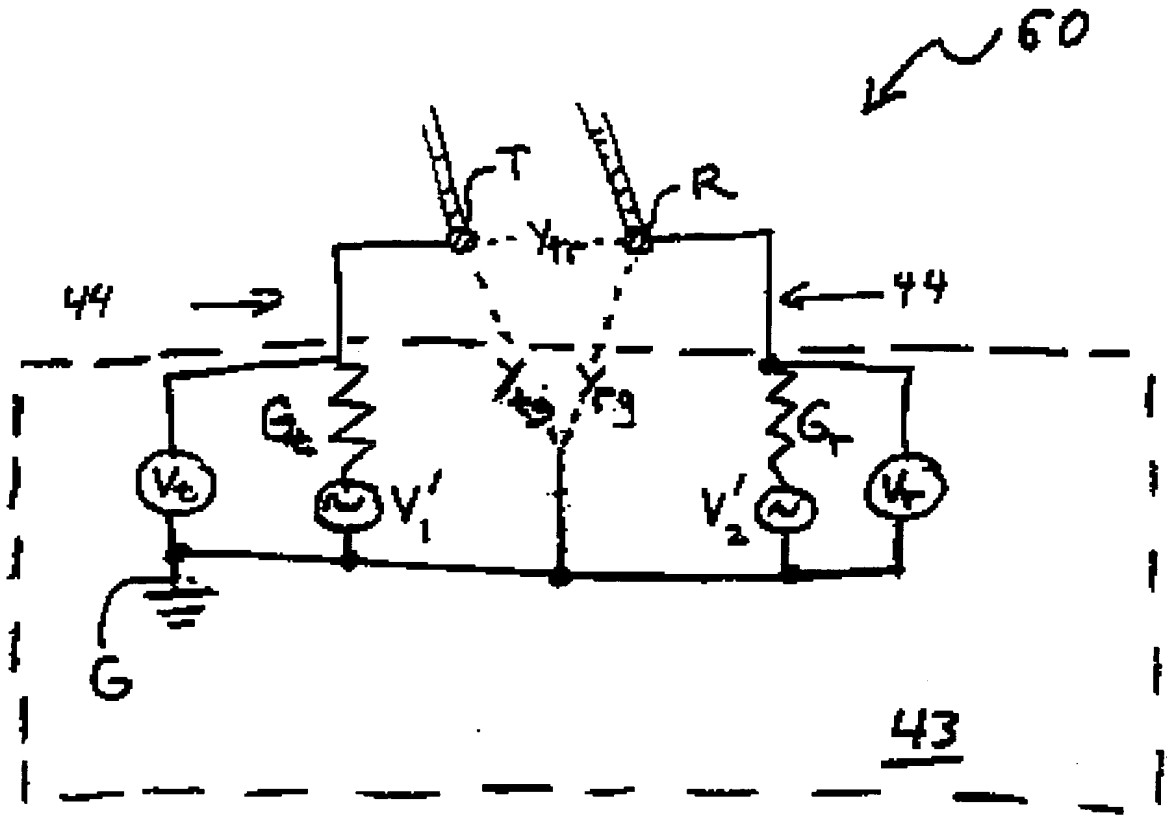


FIG. 2C

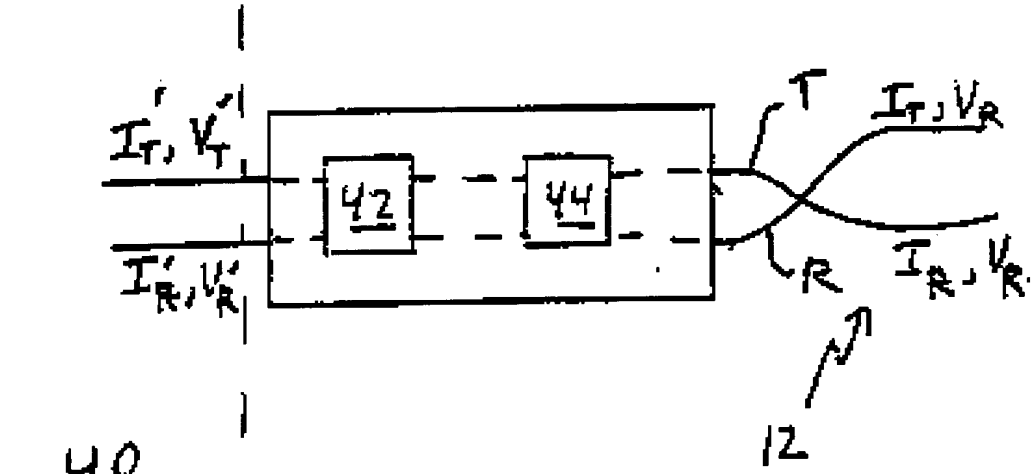


FIG. 3

BNSDOCID: <WO 0064130A2TI >

FIG. 4

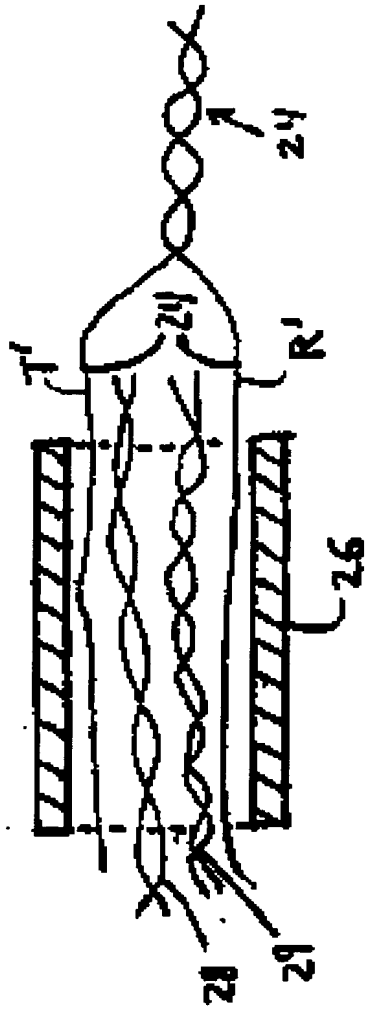
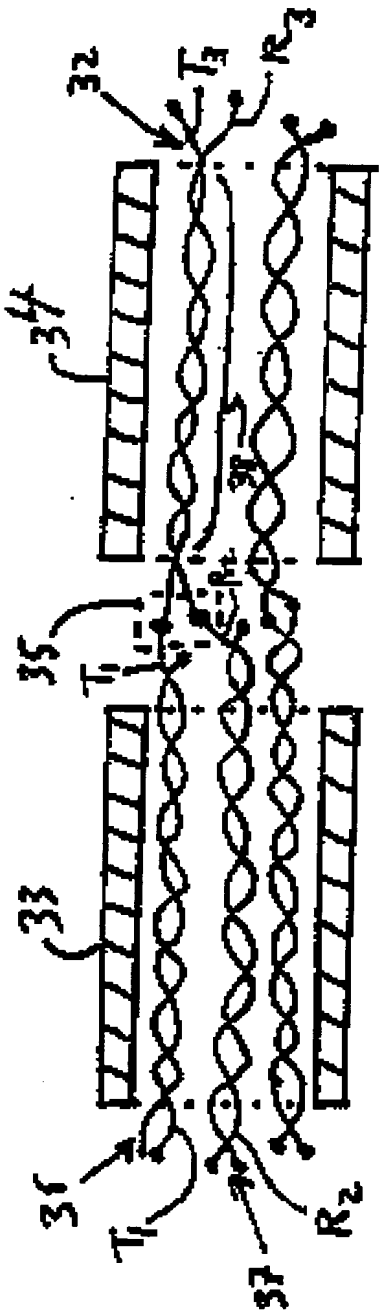


FIG. 5



BNSDOCID: <WO 0064130A2TI >

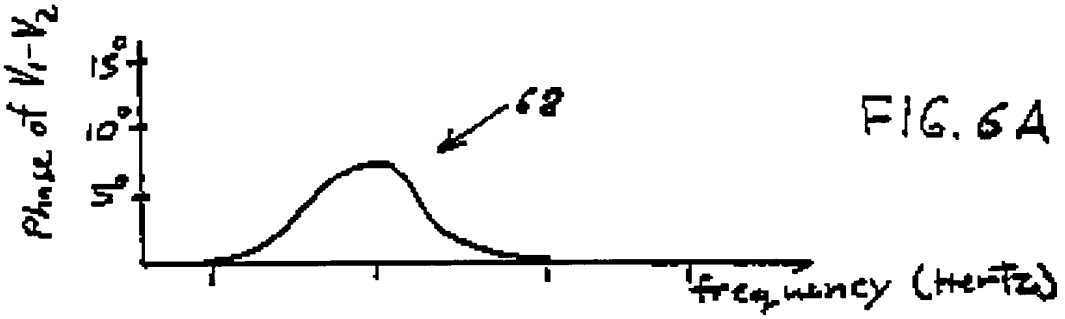


FIG. 6A

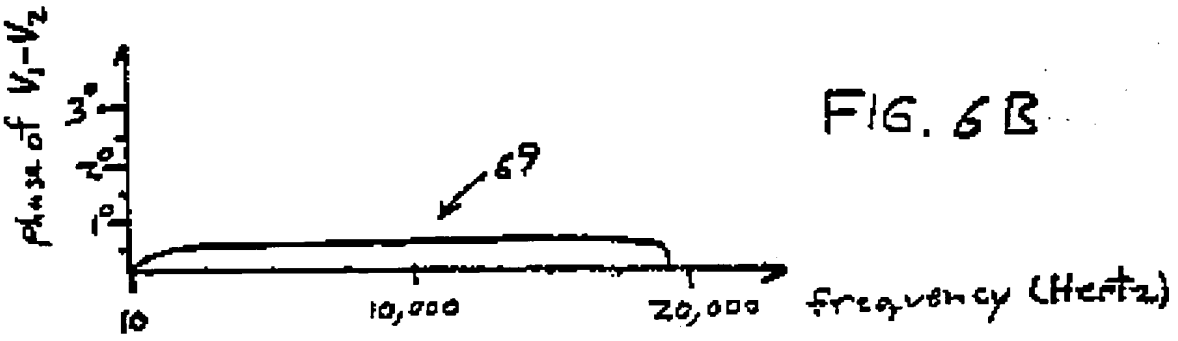
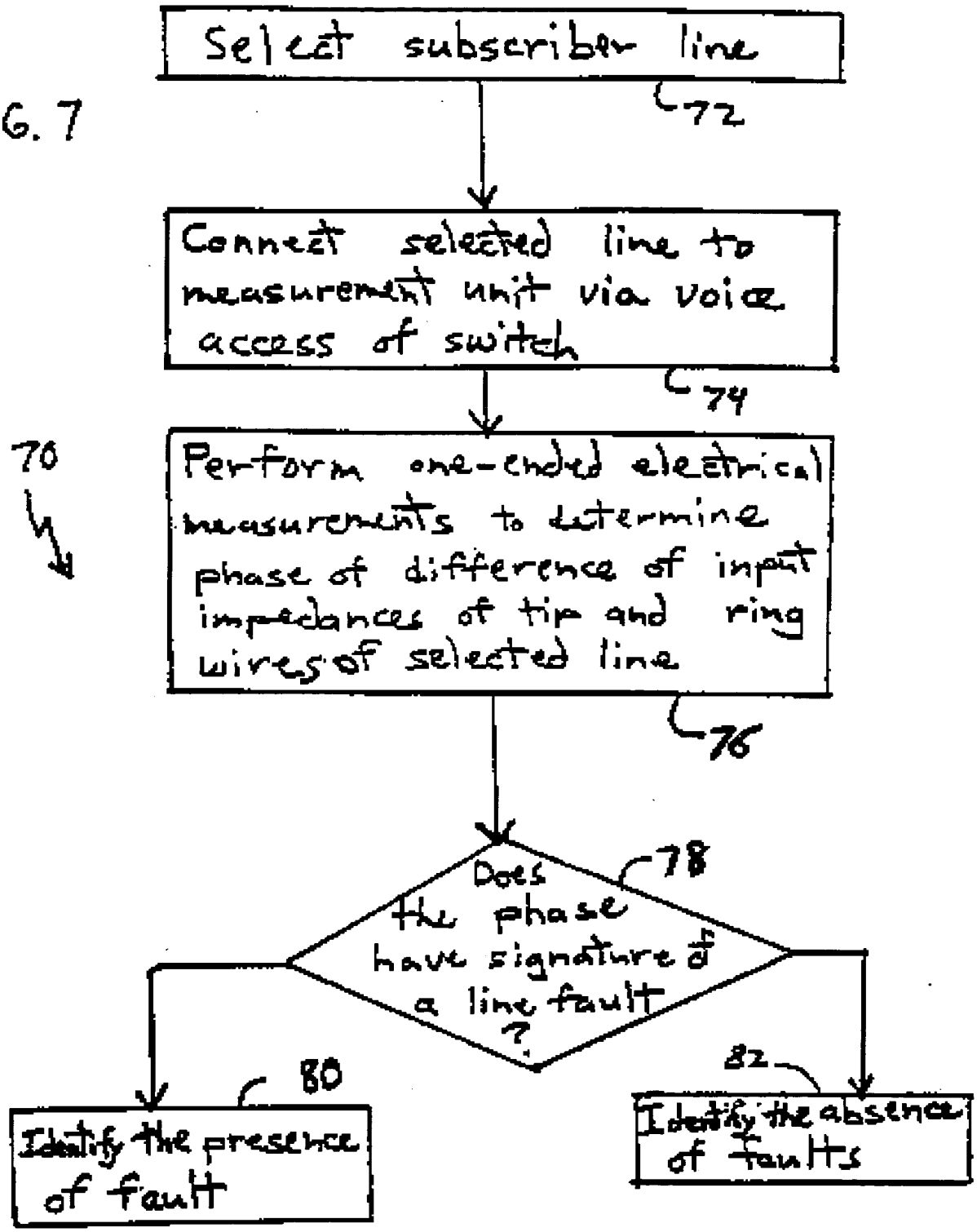


FIG. 6B

BNSDOCID: <WO 0064130A2TI >

FIG. 7


Select subscriber line
72
Connect selected line to measurement unit via voice access of switch
74
70
Perform one-ended electrical measurements to determine phase of difference of input impedances of tip and ring wires of selected line
76
Does the phase have signature of a line fault ?
78
80
Identify the presence of fault
82
Identify the absence of faults

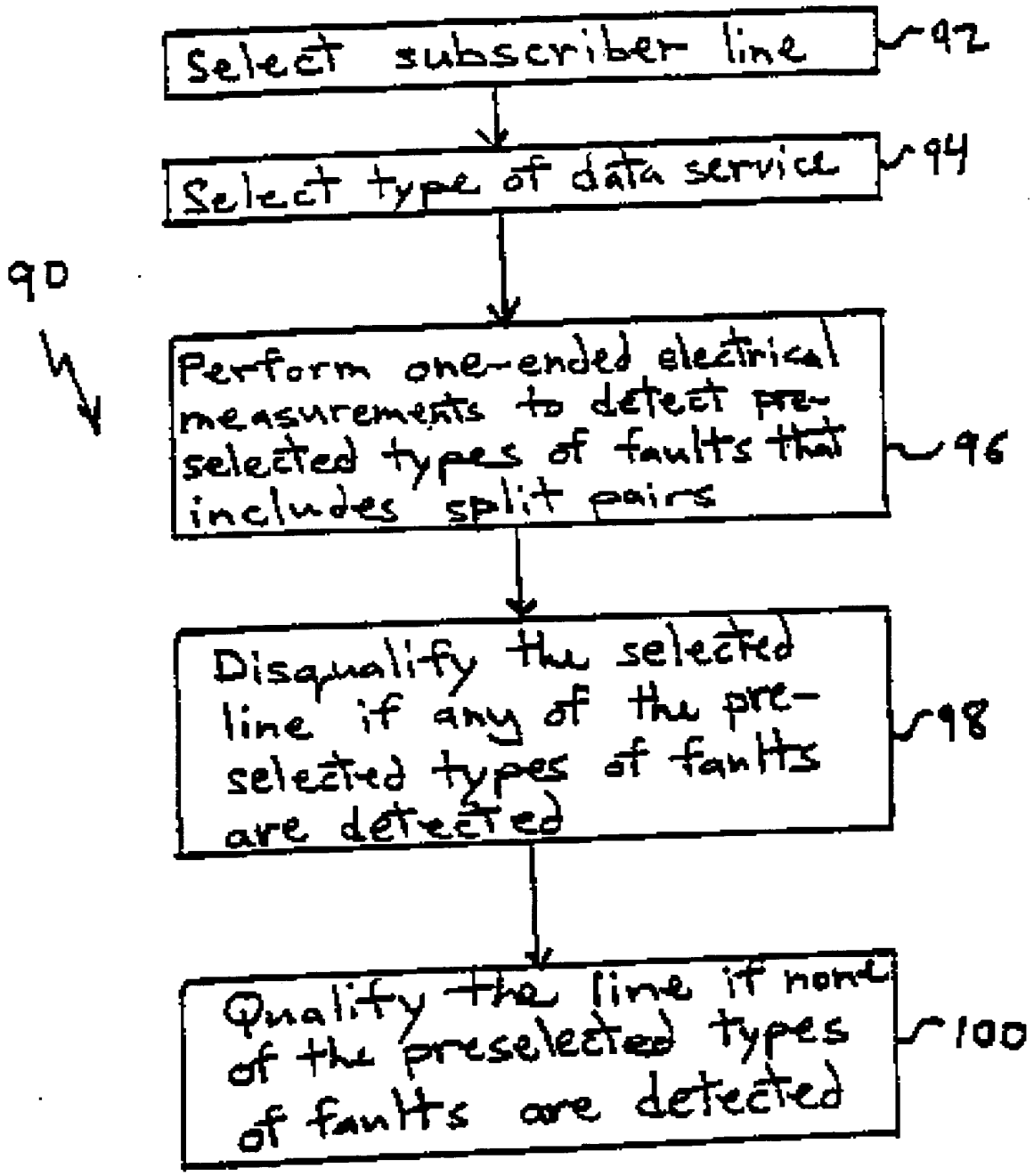


FIG. 8

BNSDOCID: <WO 0064130A2TI >

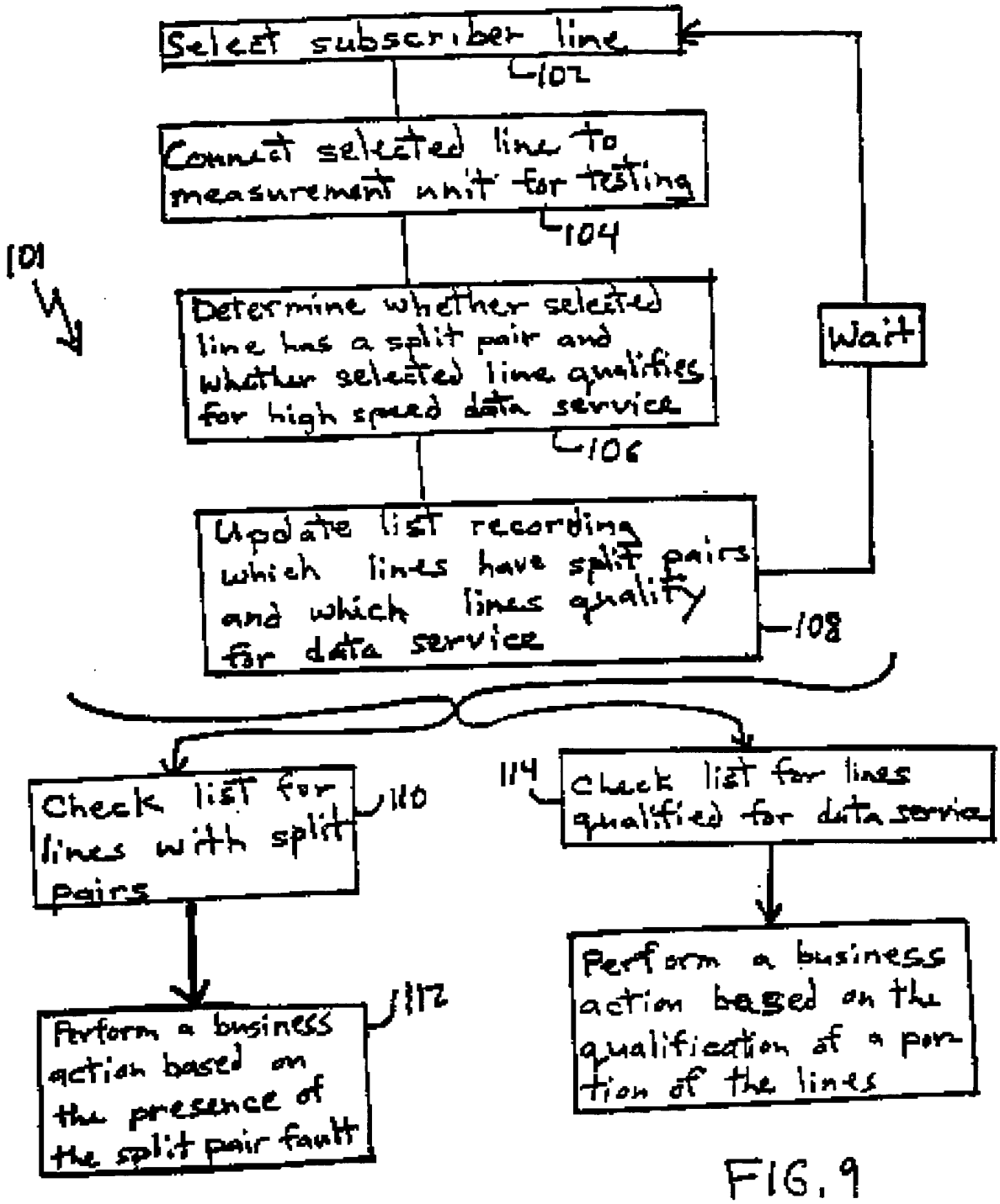

Select subscriber line
102
Connect selected line to measurement unit for testing
104
101
Determine whether selected line has a split pair and whether selected line qualifies for high speed data service
106
Wait
Update list recording which lines have split pairs and which lines qualify for data service
108
Check list for lines with split pairs
110
114
Check list for lines qualified for data service
Perform a business action based on the presence of the split pair fault
112
Perform a business action based on the qualification of a portion of the lines

FIG. 9

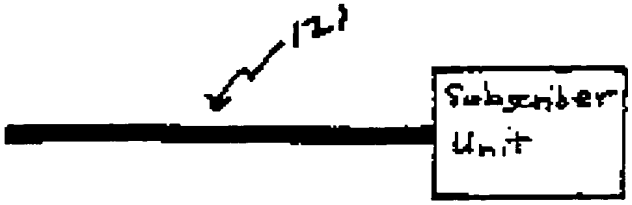


FIG. 10A

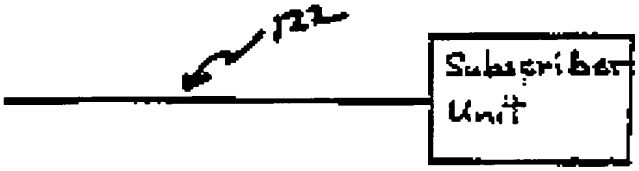


FIG. 10B

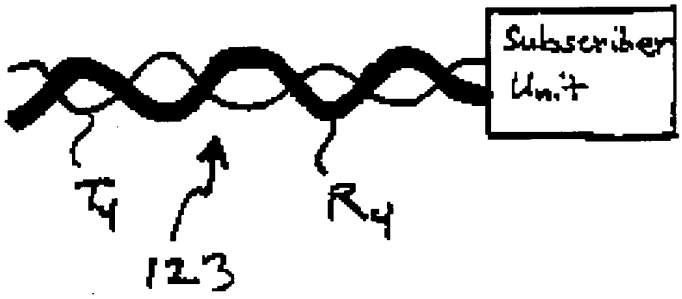


FIG. 10C

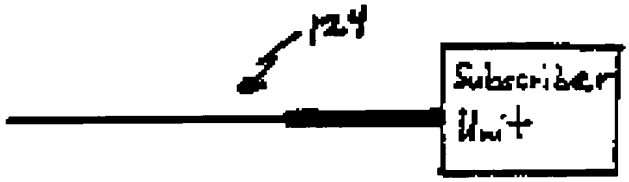


FIG. 10D

FIG. 10E

BNSDOCID: <WO 0064130A2TI >

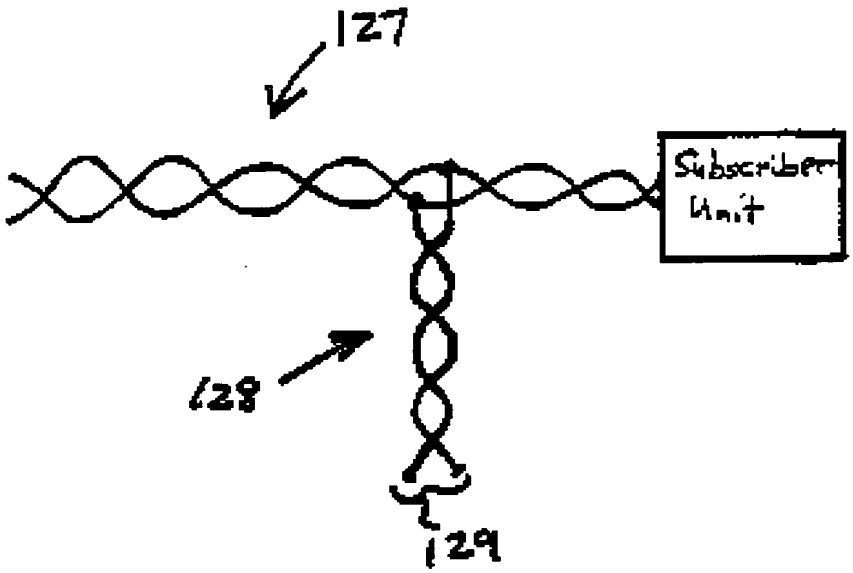


FIG. 11

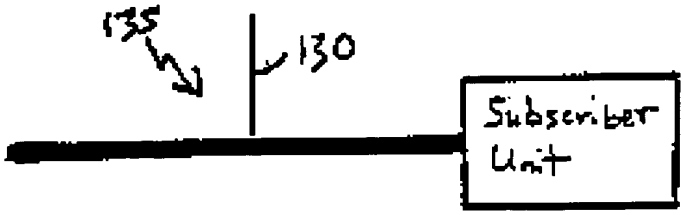


FIG. 12 A

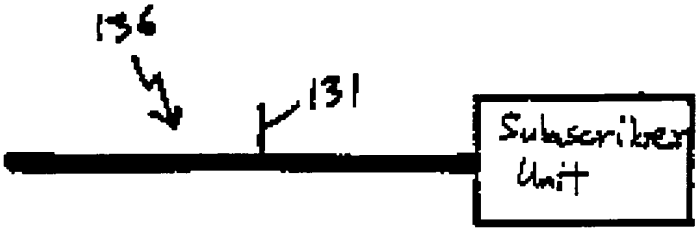


FIG. 12 B

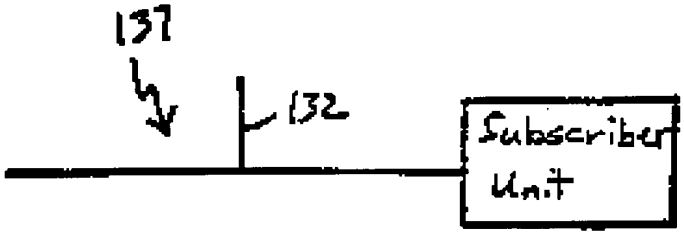


FIG. 12 C

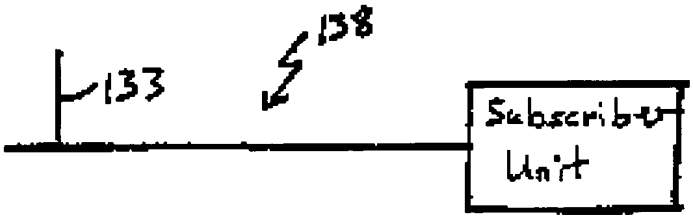


FIG. 12 D

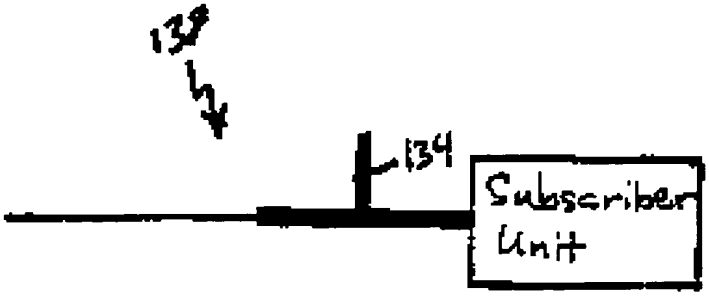


FIG. 12 E

BNSDOCID: <WO 0064130A2TI >

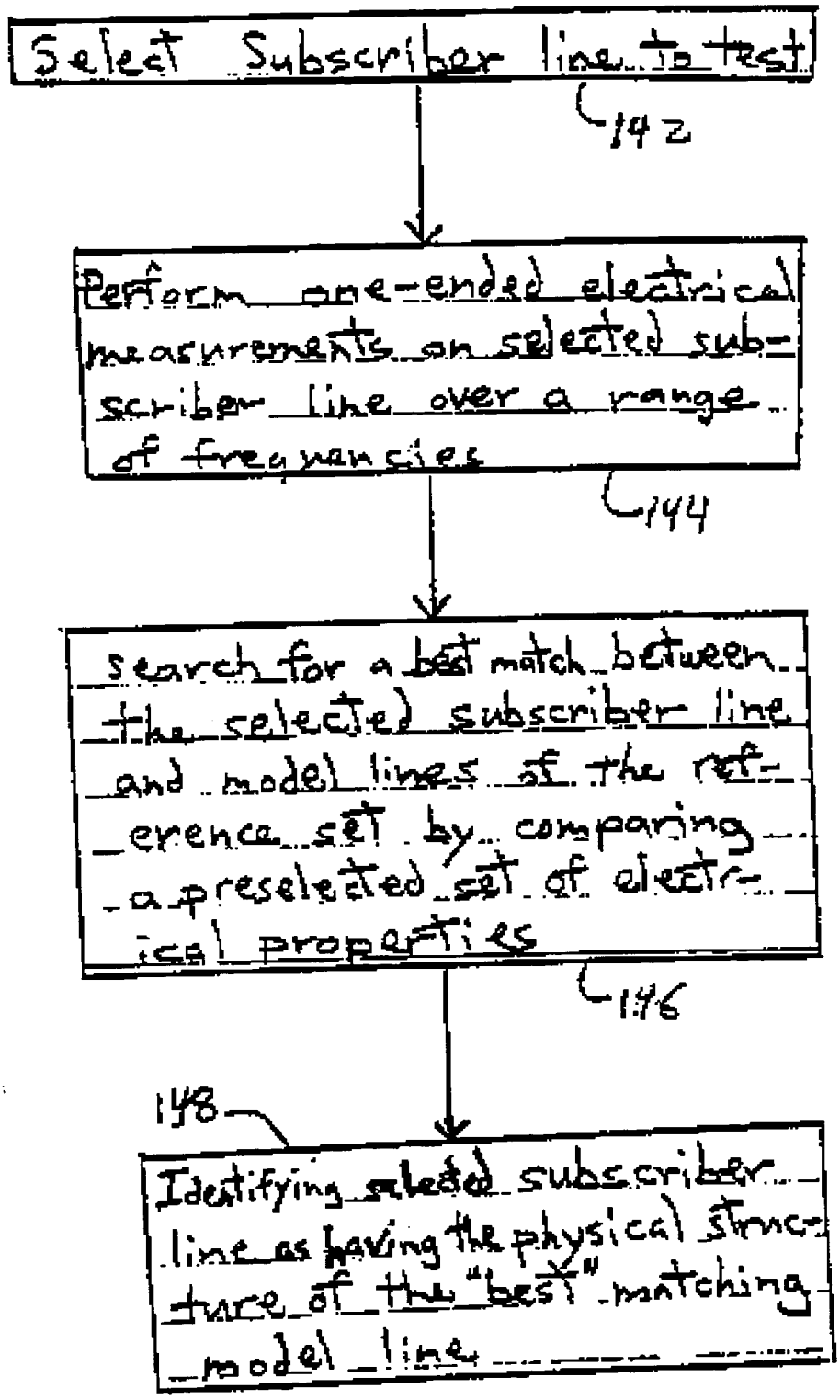


FIG. 13

BNSDOCID: <WO 0064130A2TI >

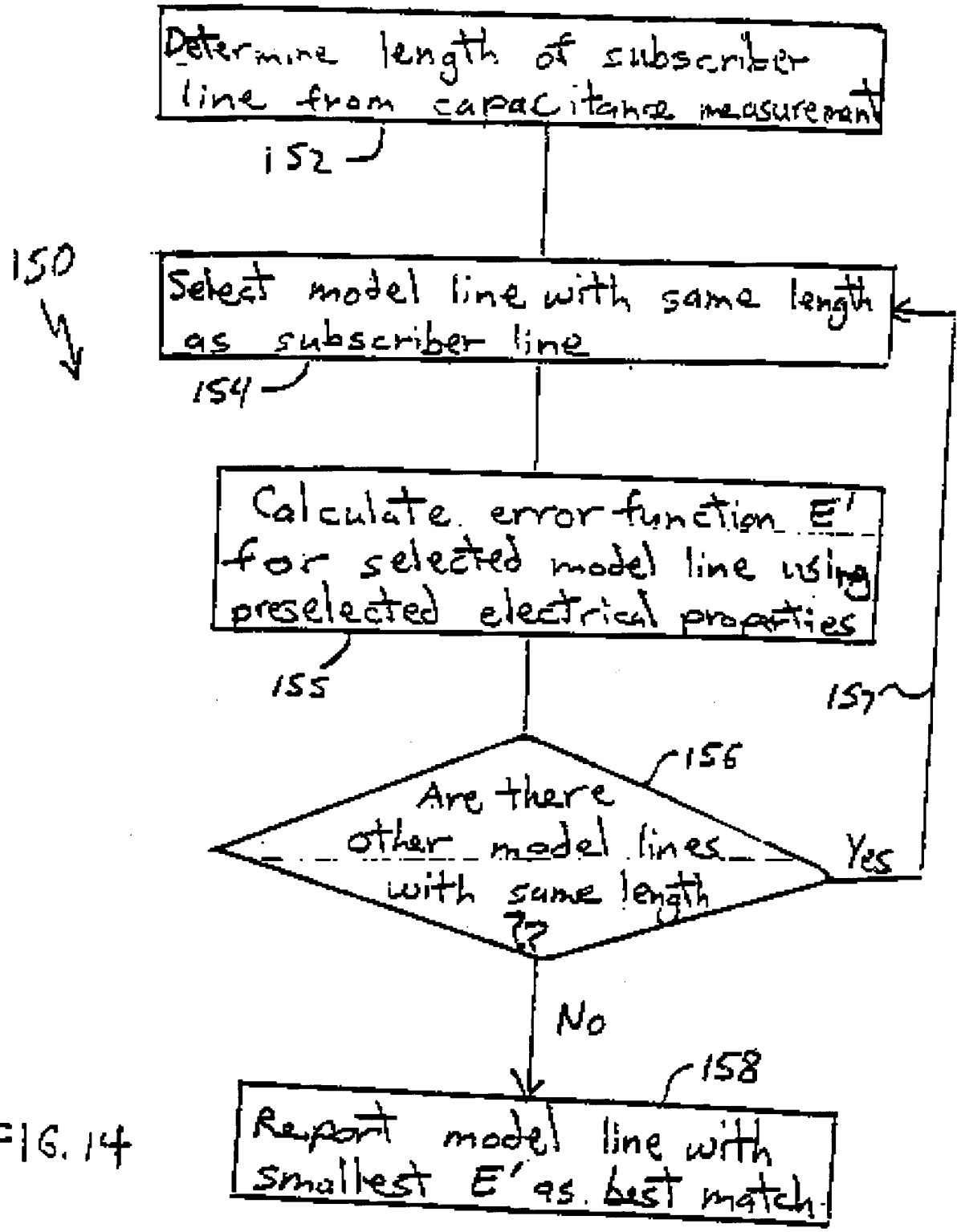


FIG. 14

BNSDOCID: <WO 0064130A2TI >

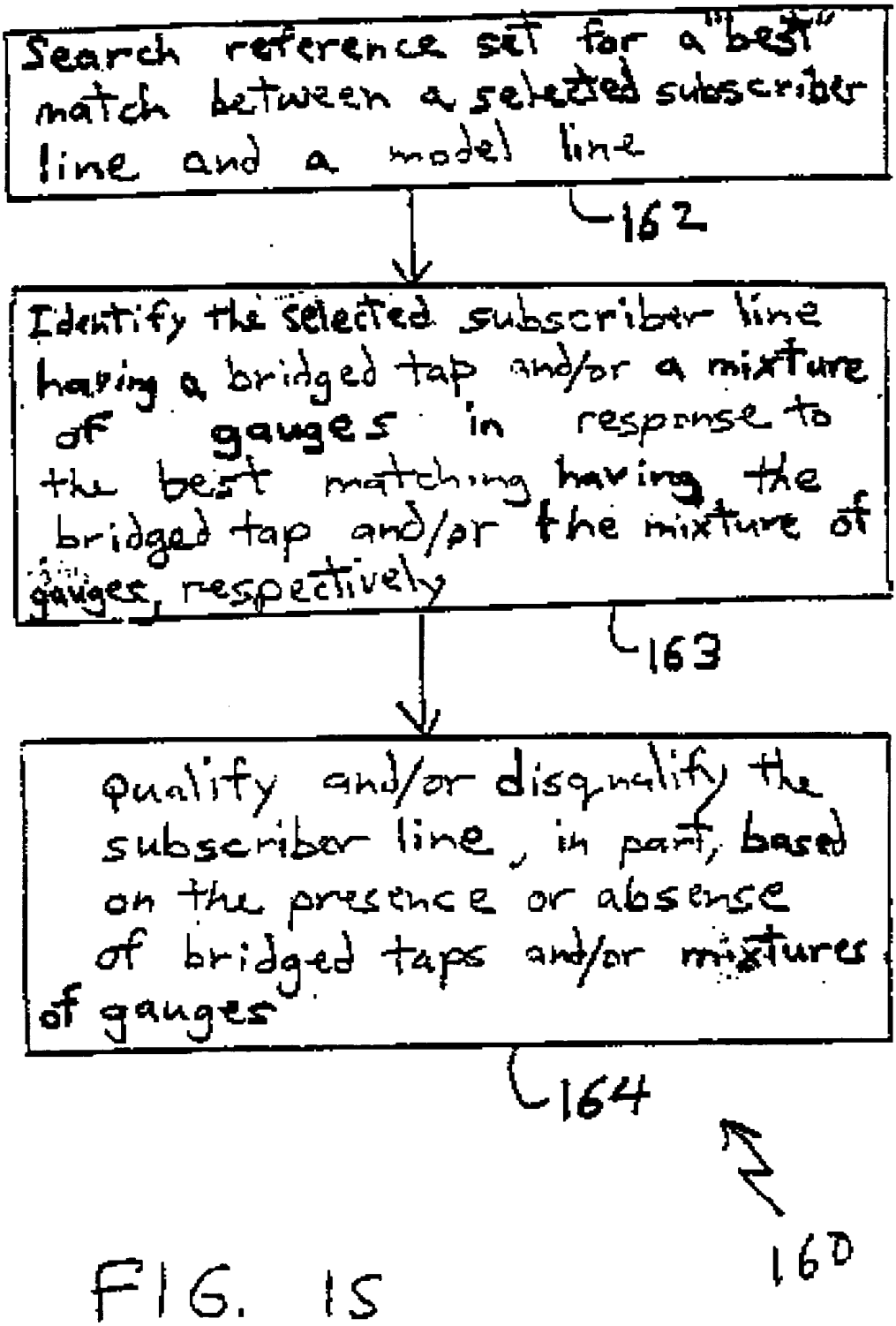

Search reference set for a "best" match between a selected subscriber line and a model line
162
Identify the selected subscriber line having a bridged tap and/or a mixture of gauges in response to the best matching having the bridged tap and/or the mixture of gauges, respectively
163
qualify and/or disqualify the subscriber line, in part, based on the presence or absence of bridged taps and/or mixtures of gauges
164
160

FIG. 15

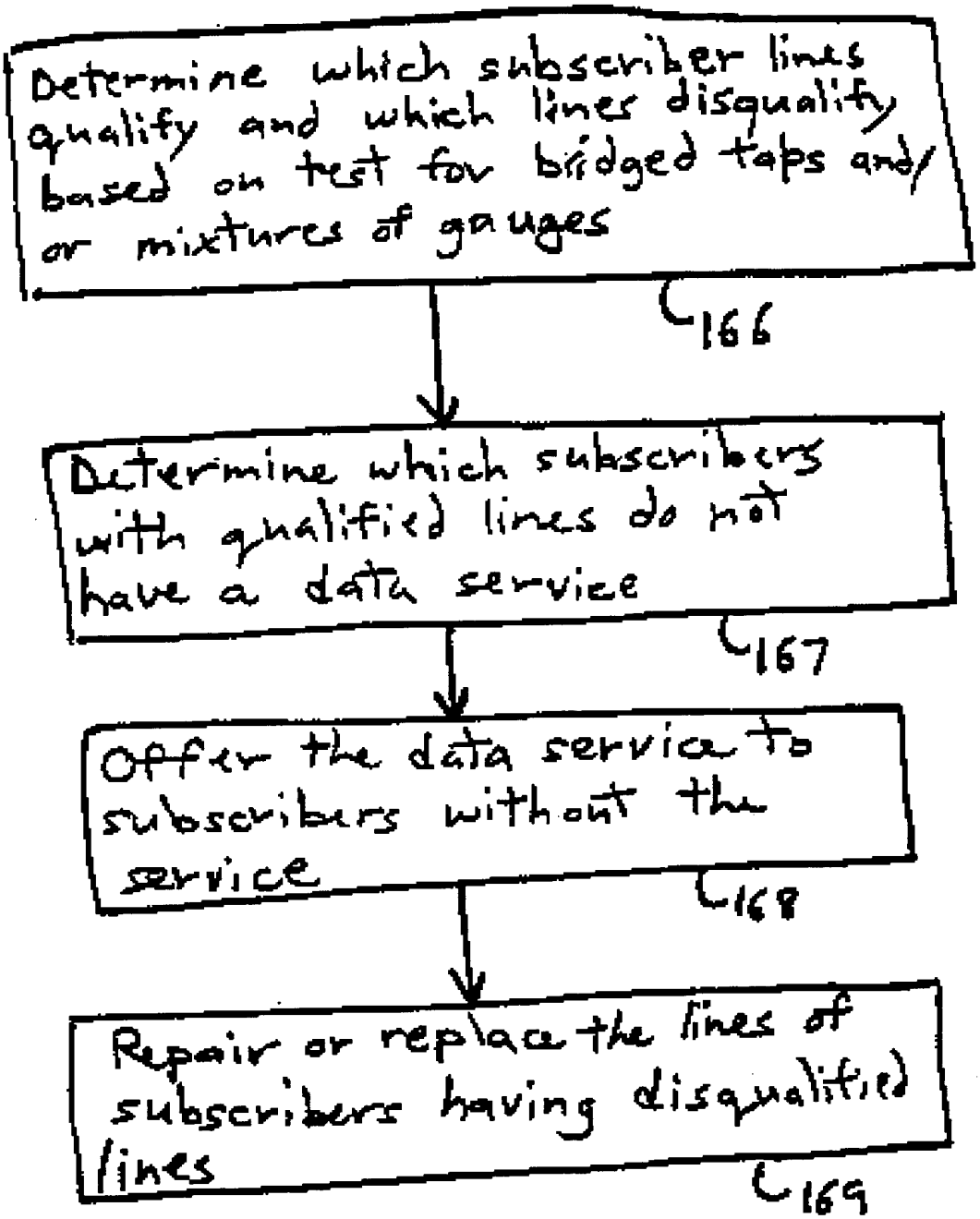


FIG. 16

BNSDOCID: <WO 0064130A2TI >

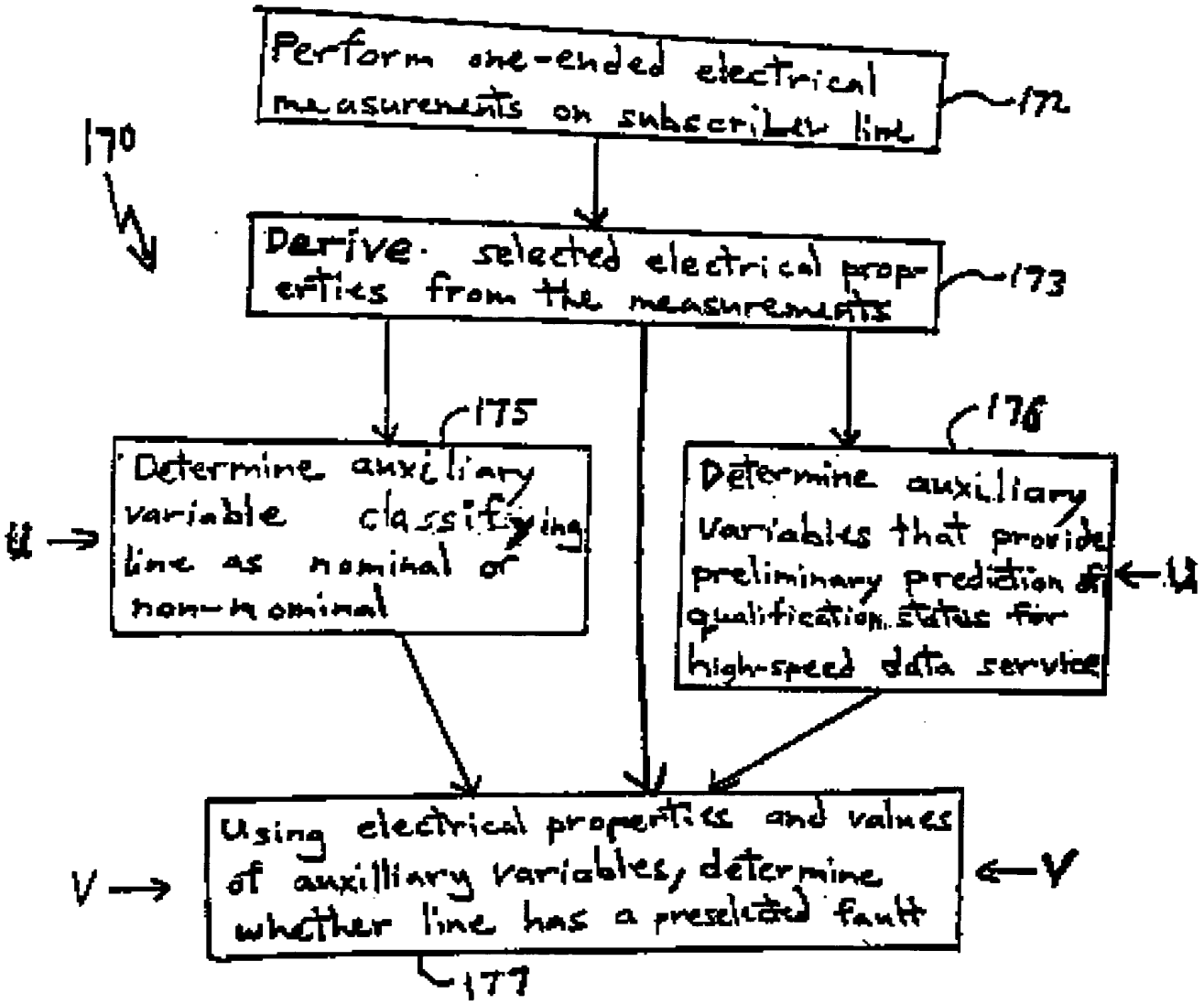


FIG. 17

BNSDOCID: <WO 0064130A2TI >

FIG. 18A

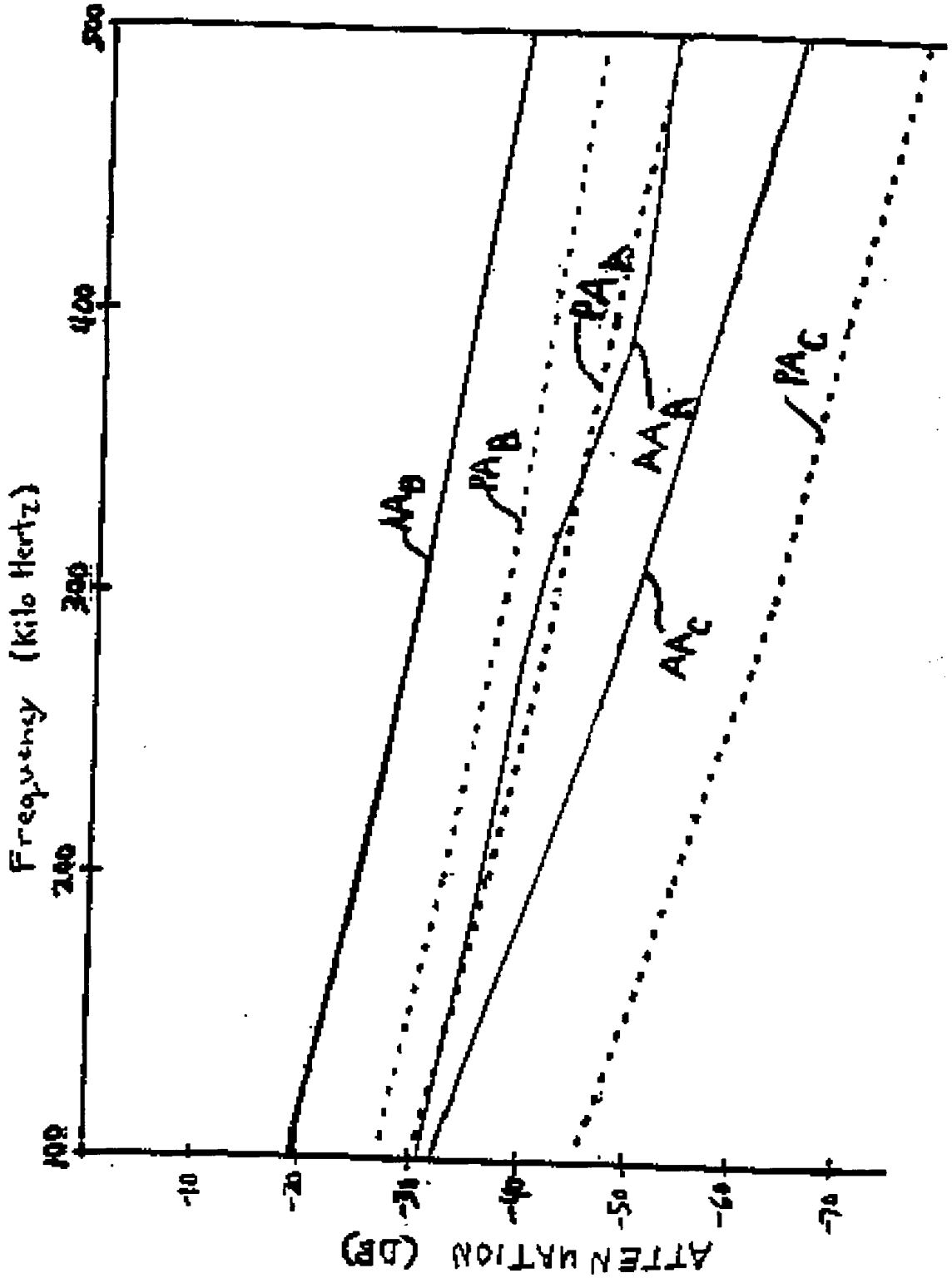


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FIG. 19B

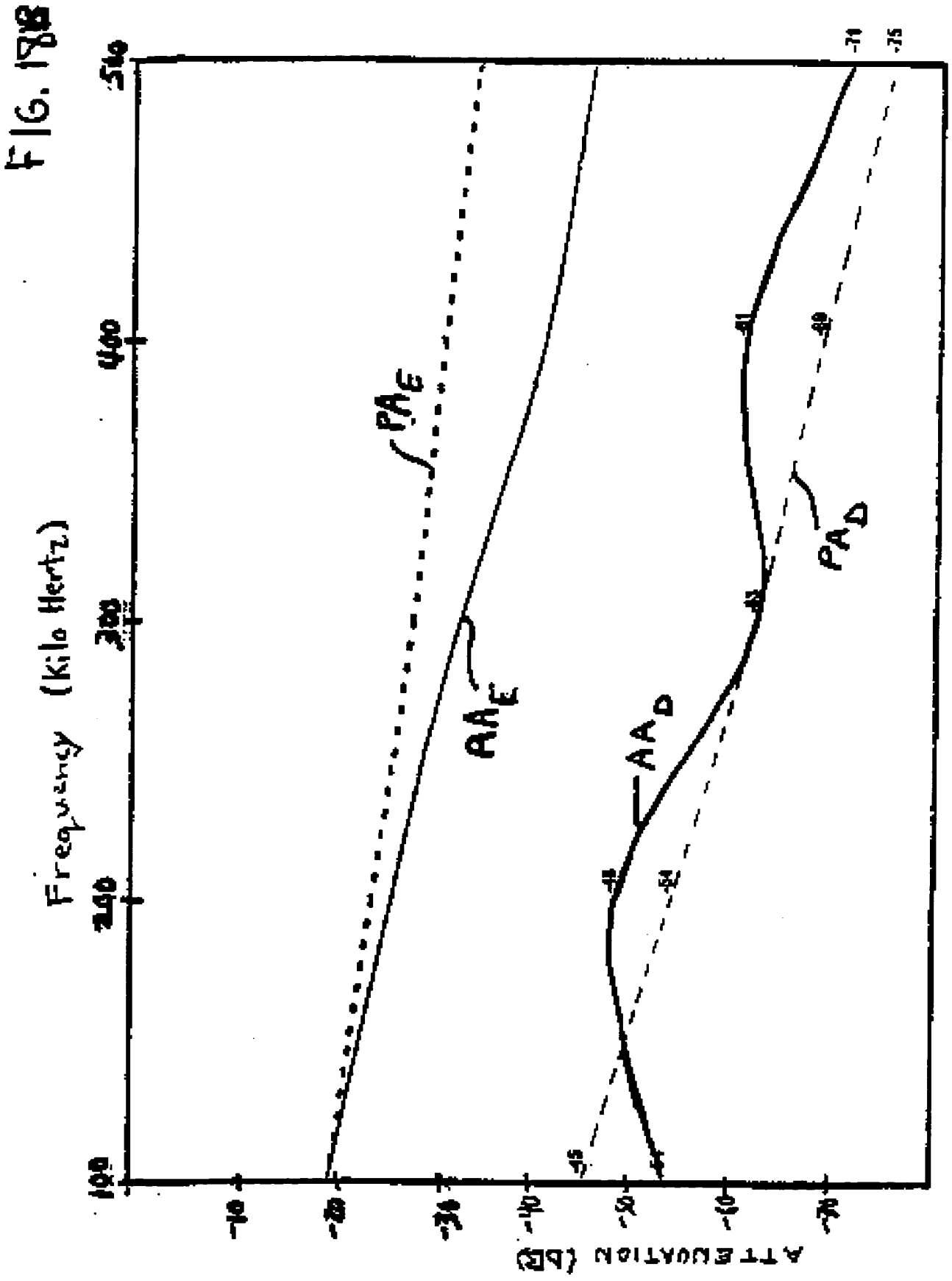

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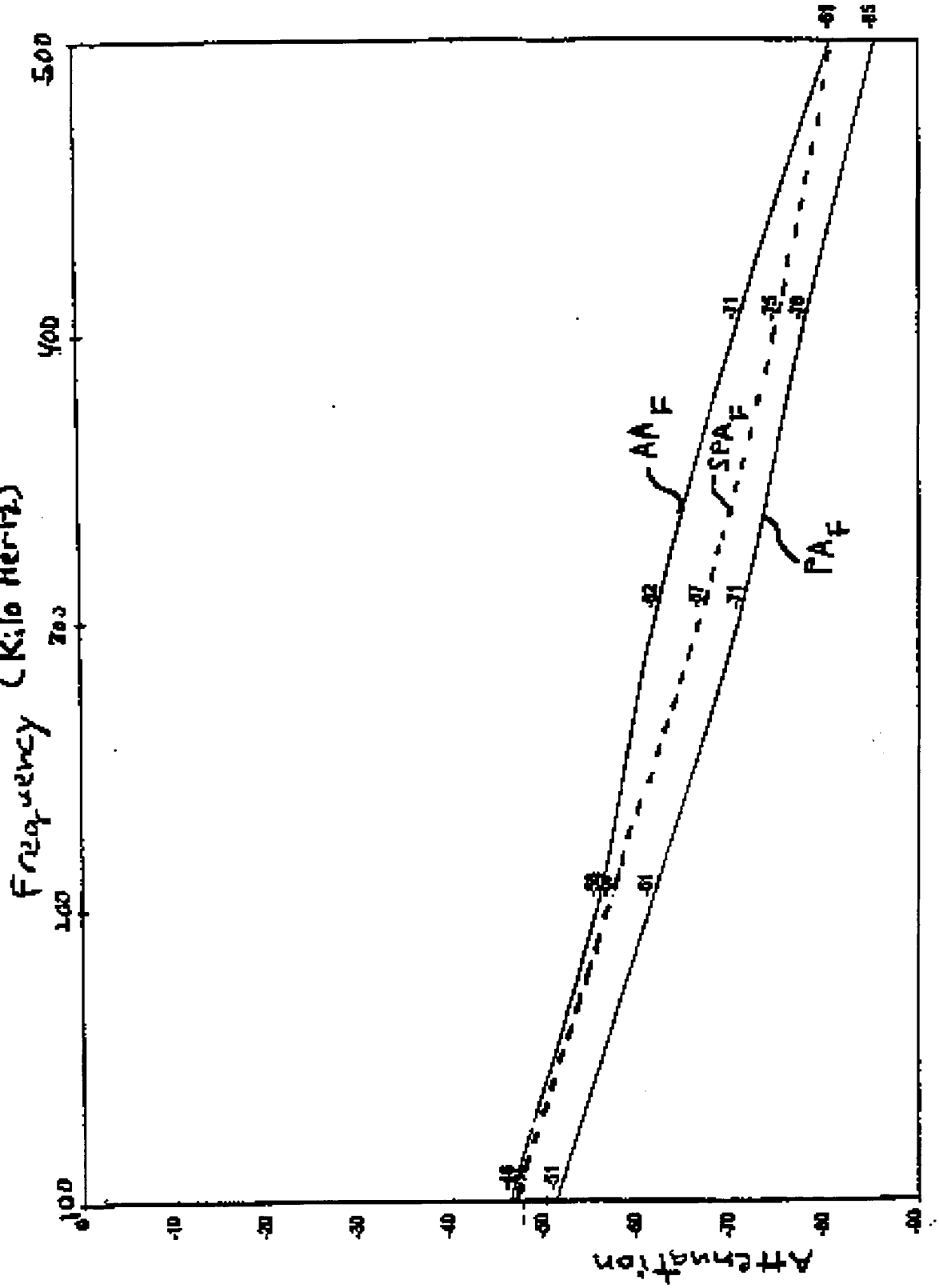
FIG. 18C



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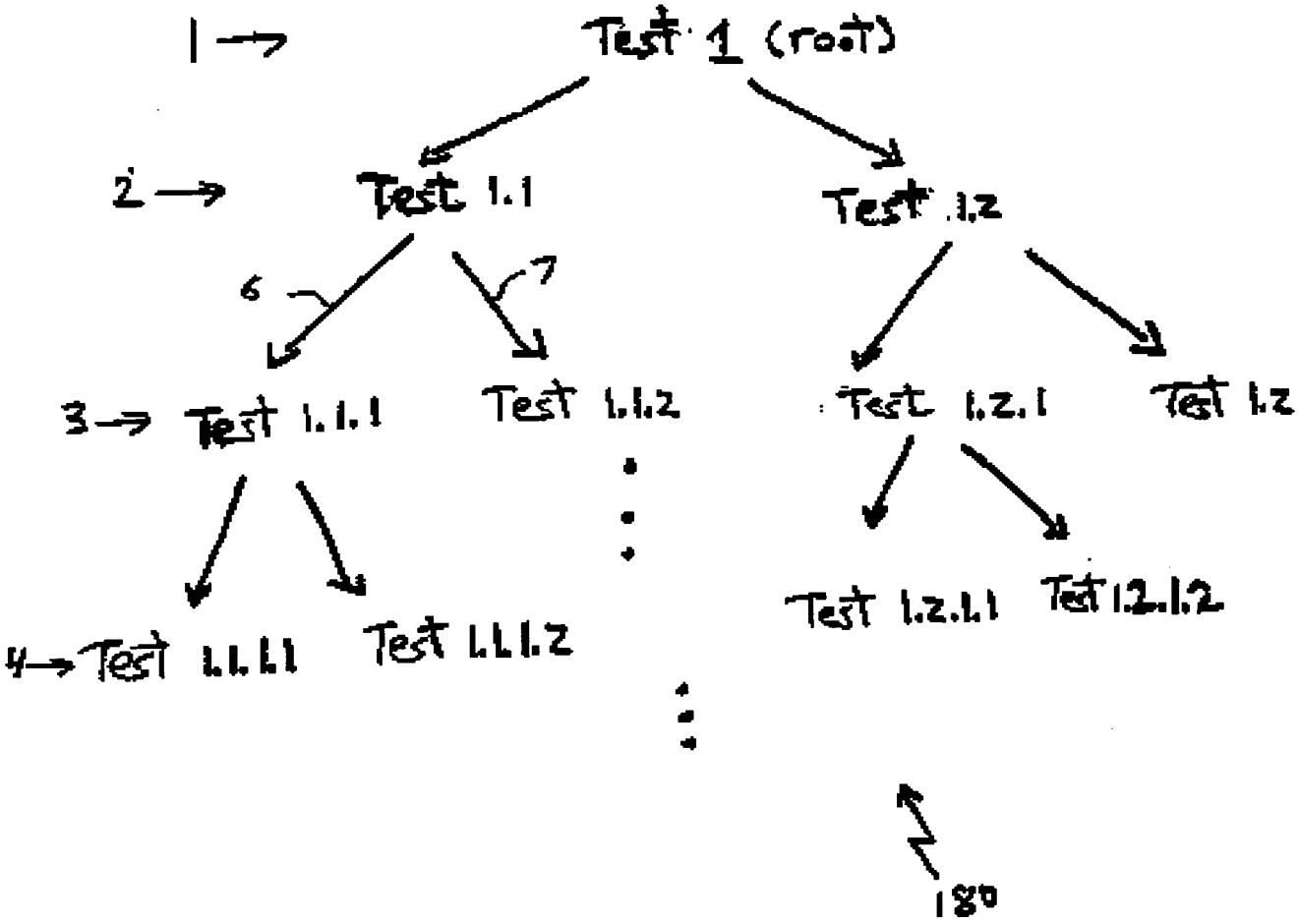
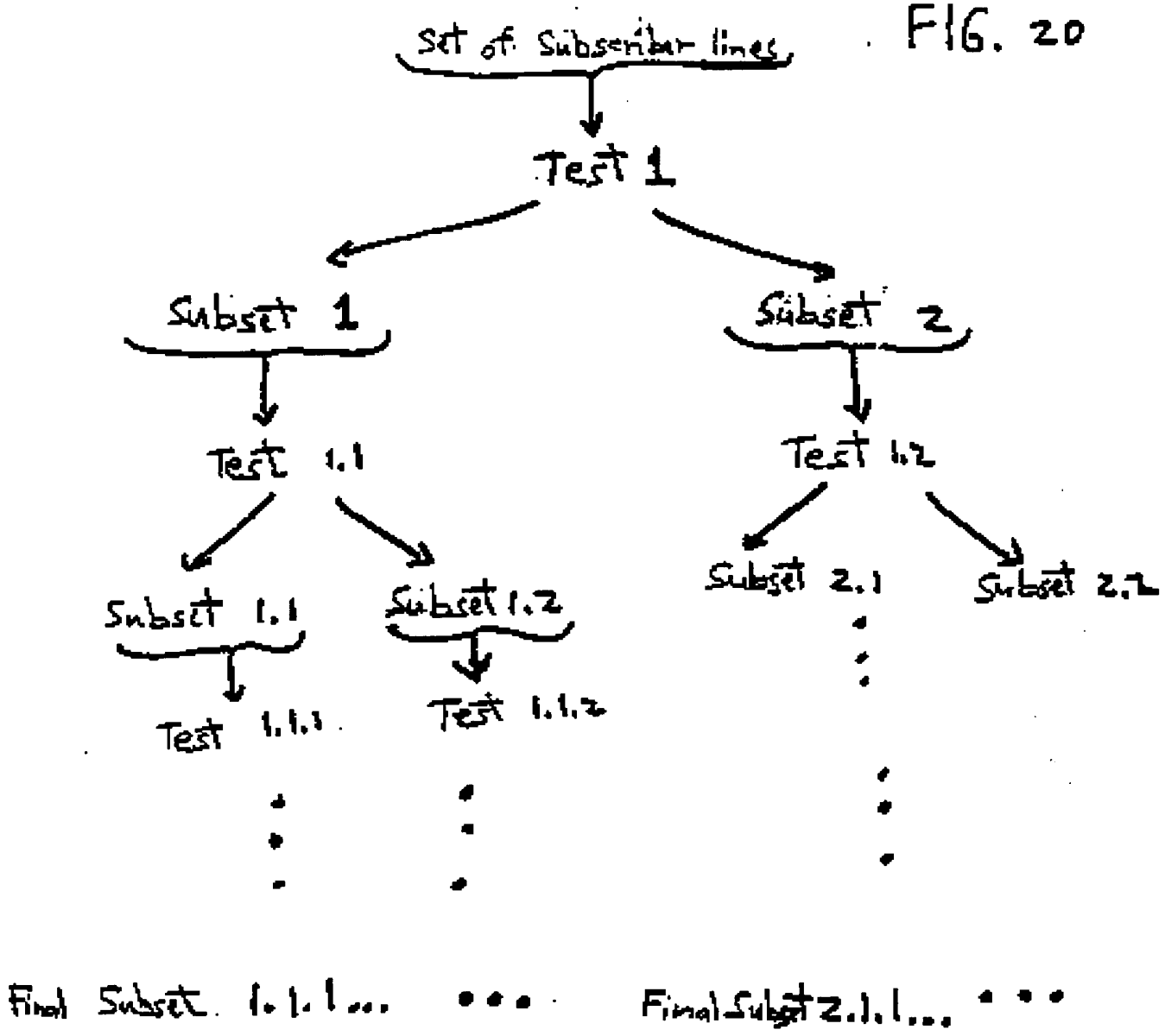


FIG. 19

BNSDOCID: <WO 0064130A2TI >

FIG. 20



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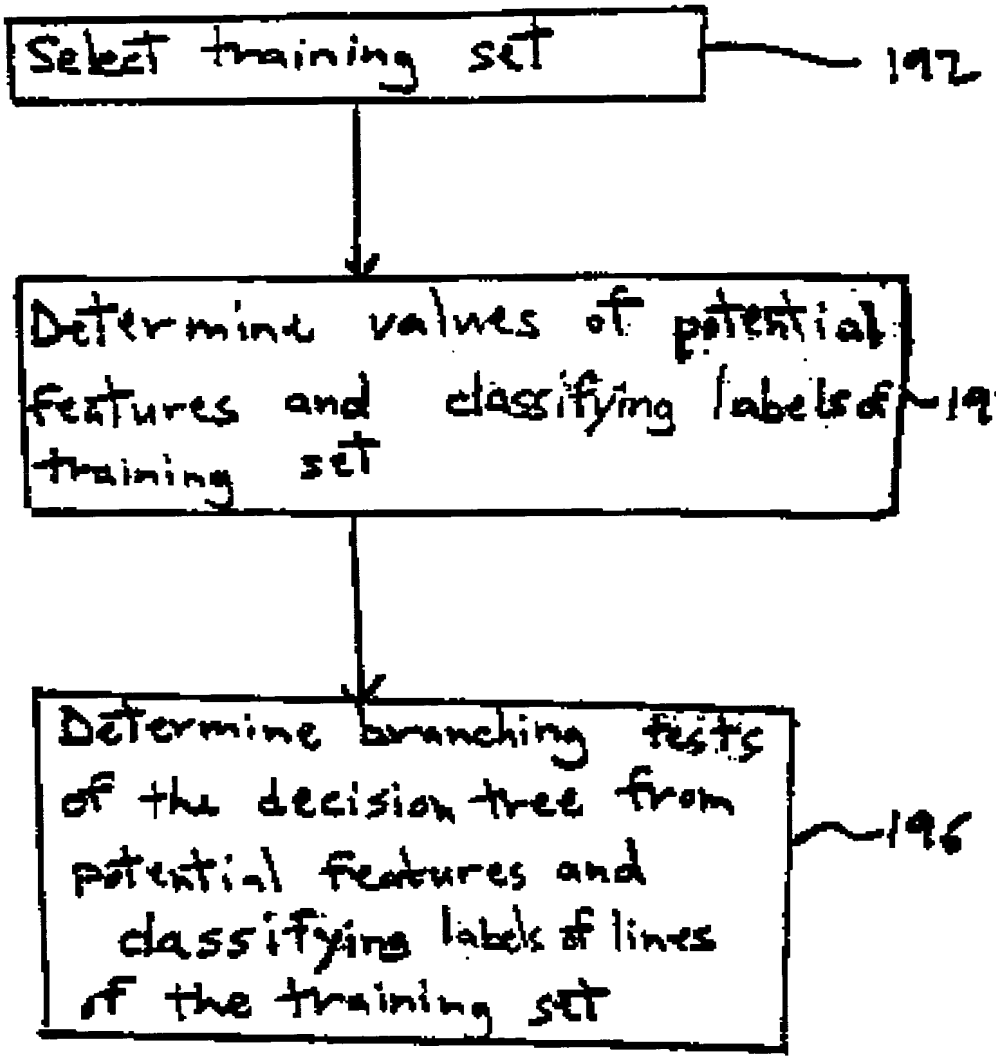

FIG. 21

BNSDOCID: <WO 0064130A2TI >

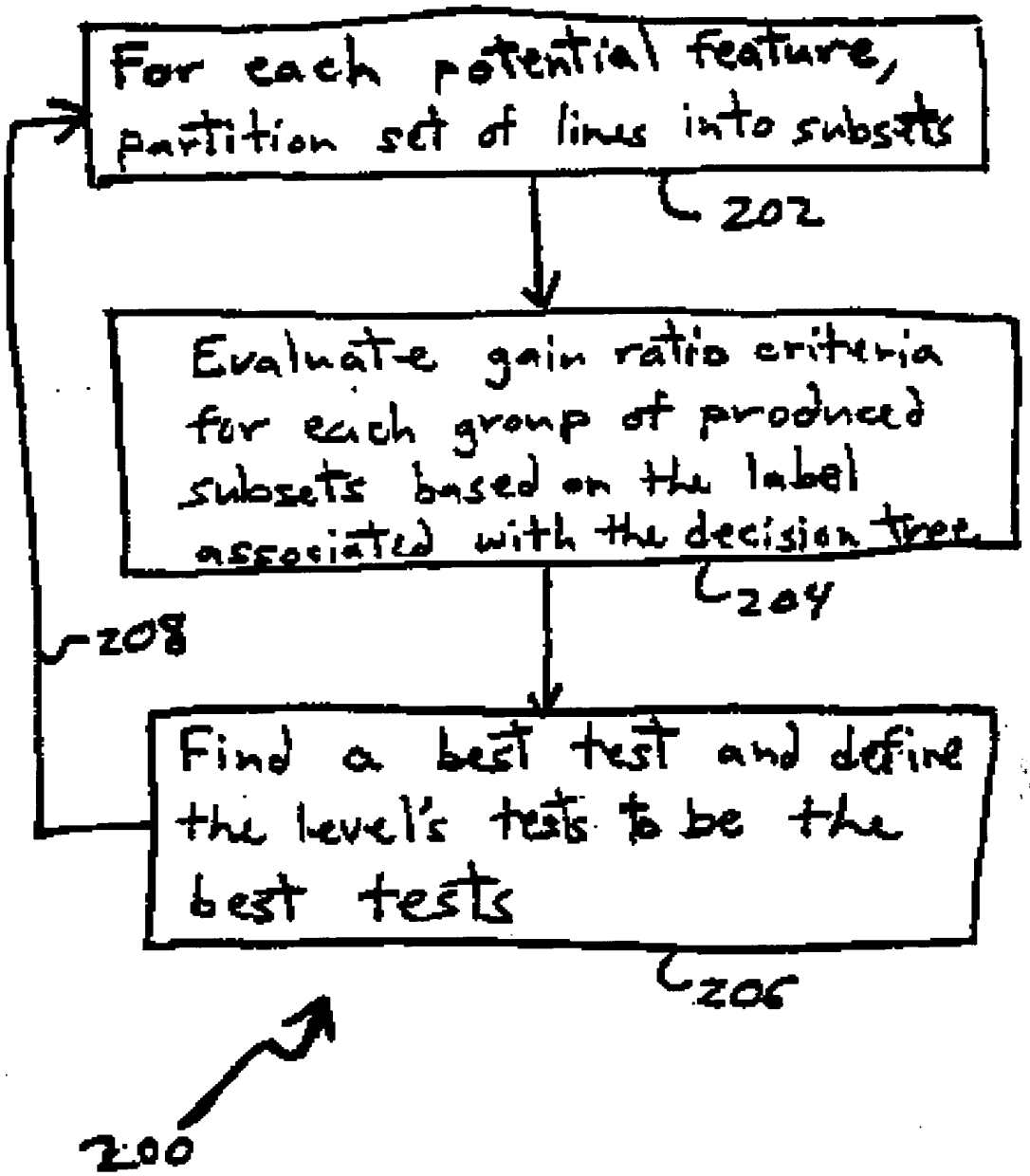

FIG. 2z

BNSDOCID: <WO 0064130A2TI >

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(25) Filing Language: English

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(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
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(88) Date of publication of the international search report:
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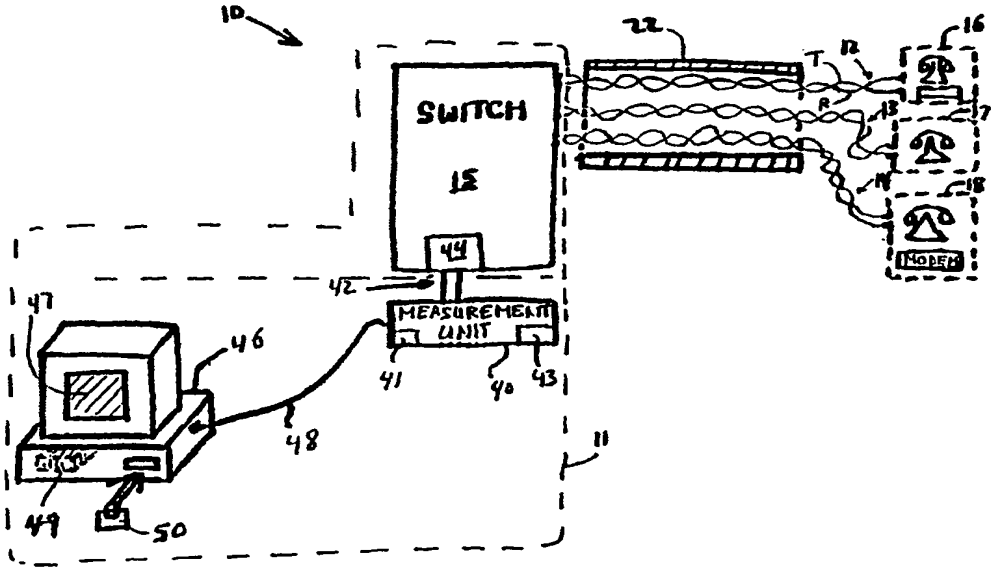
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: DETERMINING THE PHYSICAL STRUCTURE OF SUBSCRIBER LINES



(57) Abstract: A method determines a structure of a subscriber line. The method includes searching a reference set for a match between the subscriber line and a model line of the reference set and identifying that the subscriber line has a specific physical structure. The match is based on electrical properties of the lines. The act of identifying is responsive to finding a match with one of the model lines that has the specific physical structure.

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INTERNATIONAL SEARCH REPORT

Intr tional Application No
PCT/US 00/10301

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04B3/46

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04M H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 99 03221 A (ADVANCED MICRO DEVICES INC) 21 January 1999 (1999-01-21) page 15, line 28 -page 16, line 24	1,13,22, 30
A	BOETS P ET AL: "THE MODELLING ASPECT OF TRANSMISSION LINE NETWORKS" PROCEEDINGS OF THE INSTRUMENTATION AND MEASUREMENT TECHNOLOGY CONFERENCE,US,NEW YORK, IEEE, vol. -, 12 May 1992 (1992-05-12), pages 137-141, XP000343913 ISBN: 0-7803-0640-6 paragraph '0001!	1,13,22, 30

[ ] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 October 2000	10/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Cremer, J

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Int 'tonal Application No
PCT/US 00/10301

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9903221 A	21-01-1999	EP 0995287 A	26-04-2000

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